

# PHYSICAL PROPERTIES OF RADIOGRAPHIC SCREEN-FILM SYSTEMS

A study of absorption, sensitivity, noise and resolution properties of screen-film systems with fluorescent layers of various chemical compositions under exposure conditions, simulating those occurring in various diagnostic x-ray examinations

Gunnila Holje

---



Lund 1983

---





PHYSICAL PROPERTIES OF  
RADIOGRAPHIC SCREEN-FILM SYSTEMS

A study of absorption, sensitivity, noise and resolution properties of screen-film systems with fluorescent layers of various chemical compositions under exposure conditions, simulating those occurring in various diagnostic x-ray examinations

av

G U N N I L A      H O L J E  
Fil mag., Blekinge

Akademisk avhandling som med vederbörligt tillstånd av matematisk-naturvetenskapliga fakulteten vid Universitetet i Lund kommer att offentligen försvaras i föreläsningssal 1, Centralblocket, Lasarettet i Lund, onsdagen den 25 maj 1983, kl 10 15.

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  |                                                      |              |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|------------------------------------------------------|--------------|
| <b>Organization</b><br><b>LUND UNIVERSITY</b><br><br>Department of Radiation Physics<br>Lasarettet<br>S-221 85 Lund                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |  | <b>Document name</b><br><b>DOCTORAL DISSERTATION</b> |              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  | <b>Date of issue</b>                                 |              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  | <b>CODEN:</b> NFRA-1016<br>MERI-1016                 |              |
| <b>Author(s)</b><br><br>Gunnila Holje                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |  | <b>Sponsoring organization</b>                       |              |
| <b>Title and subtitle</b> PHYSICAL PROPERTIES OF RADIOGRAPHIC SCREEN-FILM SYSTEMS<br>A study of absorption, sensitivity, noise and resolution properties of screen-film systems with fluorescent layers of various chemical compositions under exposure conditions simulating those occurring in various diagnostic X-ray examinations.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |  |                                                      |              |
| <b>Abstract</b><br>This investigation, which is intended to facilitate proper selection of screen-film systems for different X-ray examinations, provides systematically evaluated data on absorption, sensitivity, noise and resolution properties of new radiographic screen-film systems.<br><br>The energy absorption in the screens was determined from measured attenuation. The sensitivity characteristics were determined in terms of the reciprocal of the energy fluence which is needed to produce a certain film density. The noise-equivalent number of absorption events was determined and its inverse was used for predictions of the quantum mottle. Radiographic mottle was evaluated by Wiener spectral analysis, and resolution capacity was evaluated in terms of modulation transfer function.<br><br>The correlation between sensitivity, noise and resolution properties of the screen-film systems reveals that a considerable reduction in patient dose can be achieved without reducing the radiographic image quality if new screen-film systems are used in a proper way. |  |                                                      |              |
| <b>Key words</b><br>X-ray intensifying screens, radiographic image quality and patient exposure, applied X-ray physics.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |  |                                                      |              |
| <b>Classification system and/or index terms (if any)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  |                                                      |              |
| <b>Supplementary bibliographical information</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |  | <b>Language</b><br>English                           |              |
| <b>ISSN and key title</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  | <b>ISBN</b>                                          |              |
| <b>Recipient's notes</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  | <b>Number of pages</b><br>36                         | <b>Price</b> |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  | <b>Security classification</b>                       |              |

Distribution by (name and address)

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature

*Gunnila Holje*

Date April 15, 1983



# PHYSICAL PROPERTIES OF RADIOGRAPHIC SCREEN-FILM SYSTEMS

A study of absorption, sensitivity, noise and resolution properties of screen-film systems with fluorescent layers of various chemical compositions under exposure conditions, simulating those occurring in various diagnostic x-ray examinations

Gunnila Holje



Lund 1983

**Life is a glittering adventure**





**To Sissa and Vidar**



# CONTENTS

Page

|                                                                                                                         |    |
|-------------------------------------------------------------------------------------------------------------------------|----|
| 1. INTRODUCTION .....                                                                                                   | 1  |
| 2. MATERIALS AND METHODS .....                                                                                          | 3  |
| 2.1 The photon attenuation by the screens                                                                               | 3  |
| 2.2 The energy absorption in the screens                                                                                | 5  |
| * The K x-ray absorption                                                                                                | 5  |
| 2.3 The screen-film sensitivity                                                                                         | 6  |
| 2.4 The light-yields of the screens                                                                                     | 7  |
| 2.5 The radiographic mottle; quantum mottle                                                                             | 7  |
| 2.6 The resolution capacity of the screen-film systems                                                                  | 8  |
| 2.7 Sensitivity, quantum mottle and resolution                                                                          | 8  |
| 3. RESULTS AND DISCUSSION .....                                                                                         | 9  |
| 3.1 The energy absorption in the screens                                                                                | 9  |
| * The K x-ray absorption                                                                                                | 12 |
| 3.2 The sensitivity of the screen-film systems                                                                          | 12 |
| 3.3 The relationship between sensitivity and energy absorption characteristics                                          | 13 |
| * Image contrast; its dependence on the chemical composition of the screen phosphor and choices of x-ray tube potential | 13 |
| * Adjustments of x-ray exposure to obtain correct film density                                                          | 15 |
| 3.4 The light-yield of the screen-film systems                                                                          | 16 |
| 3.5 Sensitivity; the balance between energy absorption and light-yield                                                  | 17 |
| 3.6 The noise-equivalent absorption in the intensifying screens                                                         | 19 |



|      |                                                                                                        |    |
|------|--------------------------------------------------------------------------------------------------------|----|
| 3.7  | Measured radiographic mottle versus predicted quantum mottle                                           | 20 |
| 3.8  | Sensitivity, noise-equivalent absorption and quantum mottle                                            | 22 |
|      | * Screen-film sensitivities at equal noise conditions                                                  | 23 |
| 3.9  | The resolution properties of the screen-film systems                                                   | 25 |
| 3.10 | The relationship between resolution and sensitivity of the screen-film systems                         | 25 |
|      | * The relationship between the resolutions and the screen-film sensitivities at equal noise conditions | 27 |
| 4.   | CONCLUSIONS .....                                                                                      | 28 |
| 5.   | ACKNOWLEDGEMENTS .....                                                                                 | 30 |
| 6.   | REFERENCES .....                                                                                       | 31 |

This thesis is based on the following papers:

- I Holje G.  
Photon attenuation by radiographic intensifying screens.  
CODEN Report LUNFD6 (NFRA-3033)/LUMEDW (MERI-3033), 1983  
To be published.
- II Holje G.  
Energy absorption in radiographic intensifying screens.  
CODEN Report LUNFD6 (NFRA-3034)/LUMEDW (MERI-3034), 1983  
To be published.
- III Holje G.  
Sensitivity characteristics of radiographic screen-film systems.  
CODEN Report LUNFD6 (NFRA-3035)/LUMEDW (MERI-3035), 1983  
To be published.
- IV Holje G.  
Radiographic mottle in screen-film systems used in diagnostic radiology.  
CODEN Report LUNFD6 (NFRA-3036)/LUMEDW (MERI-3036), 1983  
To be published.
- V Holje G.  
Energy absorption of fluorescent K x-rays produced in the phosphor layers of radiographic intensifying screens.  
CODEN Report LUNFD6 (NFRA-3037)/LUMEDW (MERI-3037), 1983  
To be published.
- VI Holje G.  
Coefficients for converting x-ray exposure to photon fluence and energy fluence.  
CODEN Report LUNFD6 (NFRA-3038)/LUMEDW (MERI-3038), 1983  
To be published.

VII Holje G. and Doi K.

MTFs and Wiener spectra of radiographic screen-film systems.

Part 2. Sensitivity, sensitometry, resolution and noise characteristics of new screen-film systems.

U.S. Department of Health and Human Services

HHS Publication FDA 82-8187, 1982

These papers will be referred to in the text as:

I : Holje (1983 a), II: Holje (1983 b),

III: Holje (1983 c), IV: Holje (1983 d),

V : Holje (1983 e), VI: Holje (1983 f),

VII: Holje and Doi (1982)

Preliminary publication:

Holje G., Svahn G., Hårdstedt C., Ramnhagen A., Öbergh A. and Forsberg H.  
Intensifying screens for x-ray cassettes, performance, usability, etc.

(In Swedish, English summary)

The Swedish Institute for the Planning and Rationalization of Health and  
Social Welfare Services, SPRI Report S 67, 1977.

Preliminary reports were given at:

The Annual Meeting of the American Association of Physicists in Medicine,  
Cincinnati, Ohio, U.S.A., 1977

The 63rd Scientific Assembly and Annual Meeting of the Radiological  
Society of North America, Chicago, Illinois, U.S.A., 1977

The Annual Meeting of the American Association of Physicists in Medicine,  
San Francisco, California, U.S.A., 1978

The 64th Scientific Assembly and Annual Meeting of the Radiological  
Society of North America, Chicago, Illinois, U.S.A., 1978



Läkarsällskapets riksstämma, Stockholm, 1979

The Annual Meeting of the American Association of Physicists in Medicine,  
Minneapolis, Minnesota, U.S.A., 1980

The 66th Scientific Assembly and Annual Meeting of the Radiological  
Society of North America, Dallas, Texas, U.S.A., 1980

Läkarsällskapets riksstämma, Stockholm, 1980

XV:th International Congress of Radiology  
Brussels, Belgium, 1981



## 1. INTRODUCTION

The conversion of incident x-ray energy into density of the film in a screen-film system includes several separate physical events. The efficiency of each event affects the total efficiency, usually referred to as the sensitivity of the screen-film system. The sensitivity of a system is thus determined by the fractional x-ray energy absorbed by the fluorescent layers of the screens, by the intrinsic efficiency of the phosphor (light energy emitted per x-ray- or electron energy absorbed), by the loss of the produced light in the system and by the film's sensitivity to the emitted light.

The development of new x-ray phosphors with higher x-ray energy-to-light energy conversion efficiency than that of conventional calcium tungstate phosphor (Buchanan et al., 1972; Stevels, 1975; Stevels and Pingault, 1975) initiated a production of more efficient x-ray intensifying screens. The high energy conversion efficiency of the new phosphors, which is achieved partly by increased intrinsic efficiency and partly by increased absorption in the photon energy range of interest in diagnostic radiology, made it possible to improve screen-film sensitivity without any increase in screen thickness. This is important, since thick screens in general have less capacity to provide high resolution. The higher intrinsic efficiency of the new phosphors may lead to considerable increases in screen-film sensitivities, but at the cost of increased quantum mottle. The higher energy absorption in the new phosphors leads to more moderate increases in screen-film sensitivities but, which is important, not at the cost of increased quantum mottle (Holje, 1983 d). From this it is obvious that it is of vital importance for the ultimate image quality whether a sensitivity increase is attained through increased energy absorption or through increased light-yield of the screens (light-energy emitted from the screen surface which is directed towards the film per x-ray energy absorbed).

The application of new intensifying screens in diagnostic radiology and their significance for reduction of patient doses has been discussed in

the literature (Degenhardt, 1980; Skucas and Gorski, 1980; Bregulla and Smidt, 1981; Thompson et al., 1977). The wide variety, however, of imaging properties introduced with the new systems has created some confusion among users, which, in turn, has resulted in a reluctance to adopt these systems in routine clinical work in spite of the significant patient dose reduction that can be achieved. It is obvious that, for full utilization of the potential of the new screen-film systems, a better understanding of their imaging performance is necessary.

Since radiographic image quality is a complex concept it is not easily quantified in terms of isolated physical properties (Rossmann, 1969). It is, however, recognized that the radiographic mottle and the resolution capacity of the screen-film system have a fundamental influence on the visibility of radiological objects (Doi et al., 1977). Effort has, therefore, been made during the last decades to attain adequate quantifications of these physical properties. Quantifications of radiographic mottle in terms of its Wiener spectrum and of resolution capacity in terms of the modulation transfer function have hereby been shown to yield close relationships with the detectability of low contrast objects and fine-detail structures, respectively (Doi and Rossmann, 1975; Rossmann and Doi, 1975; Doi et al., 1977).

Several investigations have been made of the absorption, sensitivity, noise and resolution properties of the new screen-film systems (Hollins, 1975; Rossi et al., 1976; Wagner and Weaver, 1976; Castle, 1977; Soila et al., 1977; Goodman et al., 1977; de Carvalho and Jörgensen, 1978; Rao et al., 1978; Venema, 1979). Because of the lack of standardized evaluation methods, however, (Barnard, 1982) the measured physical properties provided by different investigators and also manufacturers are often not comparable. This investigation, which is intended to facilitate proper selection of screen-film systems for different diagnostic x-ray examinations, provides systematically evaluated data on absorption, sensitivity, noise and resolution properties of new radiographic screen-film systems.



## 2. MATERIALS AND METHODS

The intensifying screens incorporated in this study are listed in Table 1. The table also gives the chemical composition of the screen phosphors, the K-absorption edge of their high Z-element(s) and the types of films used. This research on new screen-film systems began in 1976 and, therefore, the selection of intensifying screens is based on materials available at that time, but most of these are equivalent to current screens. Since many of the earliest lanthanum oxybromide screens appeared to be unstable, these screens have been modified. For this reason, therefore, the results presented here on screens made of lanthanum oxybromide may not be applicable to screens manufactured at later dates.

Since this investigation is concerned with screen-film properties in clinical situations, their physical properties have mainly been evaluated at bremsstrahlung distributions, simulating those which impinge on image recording media in various diagnostic x-ray examinations. Aluminium has been chosen to simulate human tissue, since the radiation distribution behind a certain amount of water can be simulated by the use of aluminium filters (Mika and Reiss, 1973). Twenty radiation distributions, produced at different x-ray tube potentials and with various aluminium filter thicknesses have been employed in the study (Holje, 1983 f).

### 2.1 The photon attenuation by the screens

The attenuation by the screens of photons between 20 and 120 keV, which forms the basis for the determinations of their energy absorption, was measured by use of a multichannel analyzer and a broad bremsstrahlung distribution (Holje, 1983 a). The attenuation by the intensifying screens was hereby determined simultaneously at many monoenergetic photon energies. Since the measured attenuations agree well with those calculated from tabulated mass attenuation coefficients (Storm and Israel, 1967) it can be concluded that it is quite possible to make use of broad x-ray distributions when evaluating attenuation over a wide energy range.

TABLE 1.

| Manufac-Trade name<br>turer |                   | Phosphor                                                          | Dominating<br>K-abs/keV | Film |
|-----------------------------|-------------------|-------------------------------------------------------------------|-------------------------|------|
| Agfa-<br>Gevaert            | M.R. 50           | LaOBr:Tb                                                          | 38.93                   | XRP  |
|                             | M.R. 200          | "                                                                 | "                       | "    |
|                             | M.R. 400          | "                                                                 | "                       | "    |
|                             | M.R. 600          | "                                                                 | "                       | "    |
| CAWO                        | SE 2              | LaOBr:Tb                                                          | 38.93                   | XRP  |
|                             | SE 4              | "                                                                 | "                       | "    |
|                             | SE 6              | "                                                                 | "                       | "    |
| DuPont                      | Cronex Par Sp.    | $\text{CaWO}_4$                                                   | 69.53                   | XRP  |
|                             | Cronex Quanta II  | BaFCl:Eu                                                          | 37.44                   | "    |
| Fuji                        | Grenex G-4        | $\text{Gd}_2\text{O}_2\text{S:Tb}$                                | 50.24                   | OG   |
|                             | Grenex G-8        | "                                                                 | "                       | "    |
| G.E.                        | Blue Max 1        | LaOBr:Tb                                                          | 38.93                   | XRP  |
|                             | Blue Max 2        | "                                                                 | "                       | "    |
| Ilford                      | Rare Earth        | LaOBr:Tm                                                          | 38.93                   | XRP  |
| Kodak                       | X-Omatic Reg.     | $\text{BaSO}_4\text{:Eu/SrSO}_4\text{:Eu}$                        | 37.44/16.11             | XRP  |
|                             | Lanex Fine        | $\text{Gd}_2\text{O}_2\text{S:Tb}$                                | 50.24                   | OG   |
|                             | Lanex Reg.        | $\text{Gd}_2\text{O}_2\text{S:Tb/La}_2\text{O}_2\text{S:Tb}^{1)}$ | 50.24/38.93             | "    |
| Philips                     | Type 4360         | BaFCl:Eu                                                          | 37.44                   | XRP  |
|                             | Type 6359         | "                                                                 | "                       | "    |
| Siemens                     | Rubin Super       | $\text{CaWO}_4$                                                   | 69.53                   | XRP  |
|                             | Titan 923         | LaOBr:Tb                                                          | 38.93                   | "    |
| 3M                          | Trimax Alpha 4    | $\text{Gd}_2\text{O}_2\text{S:Tb}$                                | 50.24                   | OG   |
|                             | Trimax Alpha 8    | "                                                                 | "                       | "    |
| U.S.<br>Radium              | Rarex BG Detail   | $\text{Gd}_2\text{O}_2\text{S:Tb/Y}_2\text{O}_2\text{S:Tb}^{2)}$  | 50.24/17.04             | OG   |
|                             | Rarex BG Mid Sp.  | $\text{Gd}_2\text{O}_2\text{S:Tb/Y}_2\text{O}_2\text{S:Tb}^{3)}$  | 50.24/17.04             | "    |
|                             | Rarex BG High Sp. | "                                                                 | "                       | "    |
|                             | Rarex B Mid Sp.   | $\text{Y}_2\text{O}_2\text{S:Tb}$                                 | 17.04                   | XRP  |

The films are manufactured by Eastman Kodak Co.

1) 93 %/ 7 % by weight 2) 60 %/ 40 % by weight, 3) 75 %/ 25 % by weight.

## 2.2 The energy absorption in the screens

The energy absorption in the screens of monoenergetic radiation was determined from measured attenuation by employing tabulated mass attenuation coefficients (Storm and Israel, 1967). Photoelectric absorption alone was considered and the partial absorption of internally produced K x-rays was taken into account (Holje, 1983 b). The mean energy absorptions in the screens at the various bremsstrahlung distributions studied were obtained by weighting their monoenergetic responses according to the energy fluence distributions.

The K x-ray absorption. The high energy absorption in most of the new screens was shown to be an immediate consequence of the favourable location of the K-absorption edge of their high Z-element (Holje, 1983 b). The energy intervals where these phosphor screens have maximal energy absorption coincide well with those where many of the differential energy fluence distributions, encountered in diagnostic radiology, are the highest. The high frequency of K-shell interactions in these screens, however, leads to high production of K x-rays. The consequent high absorption of K x-ray energy has been shown to be disadvantageous for the resolution properties (Karlsson et al., 1977; Arnold and Bjärngård, 1979). In spite of this unfavourable condition, the measured resolutions of the new screen-film systems are definitely superior to those of conventional calcium tungstate systems with comparable sensitivity (Holje et al., 1977; Holje and Doi, 1982). Absorption of K x-rays, however, seems to be advantageous to the quantum mottle in screen-film systems (Vyborny et al., 1982). Aiming at a better understanding of its influence on the sensitivity, noise and resolution properties of screen-film systems, a quantification of K x-ray energy absorption was made (Holje, 1983 e).

In connection with determinations of attenuation and energy absorption of K x-rays, which are emitted from the highest Z-element of the phosphors, a simple empirical relationship was established between the attenuation of internally produced K x-rays,  $A_K$ , and the attenuation by the screens of perpendicularly incident photons of equivalent energy,  $A_{h\nu=K}$ , (Holje, 1983 e):

$$\log A_K = 0.67 \cdot \log (A_{h\nu=K}) - 0.079$$

To give due proportions to the absorption of K x-ray energy in the screens, it was related to the total energy absorption of incident photons. This determination was performed for monoenergetic photons (Holje, 1983 e), as well as for bremsstrahlung distributions (Holje, 1983 b). These ratios are expected to be applicable to predictions of the influence of absorbed K x-rays on the quantum mottle and the resolution properties of the screen-film systems.

### 2.3 The screen-film sensitivity

Since the absorption characteristics of the new x-ray phosphors differ from those of calcium tungstate phosphor, the energy dependence of the sensitivity of the new screen-film systems cannot be expected to be the same as that of conventional calcium tungstate systems. The implication of this is that the new systems may exhibit image contrast, sensitivity to scattered radiation (Castle, 1977) and response to changes in x-ray tube potential, which are entirely different from those of calcium tungstate systems. By performing a detailed analysis of the sensitivity characteristics of the screen-film systems, it is possible to comprehend these differences. Knowledge of their sensitivity characteristics will also facilitate improvements in image quality and/or patient exposure by selecting appropriate screen-film systems in different diagnostic examinations.

A comprehensive analysis of the sensitivity characteristics of the screen-film systems has been performed (Holje, 1983 c). The sensitivities at various bremsstrahlung distributions were determined from measured x-ray exposures, needed to produce a net film density of 1.0. By use of conversion coefficients (Holje, 1983 f) these exposure values were converted into the corresponding energy fluences, the reciprocal of which were employed as measures of the sensitivities.

Knowledge of the energy absorption in the screens and the sensitivity of the screen-film systems made it possible to determine the energy deposi-



ted per unit screen area for production of a film density of 1.0 (Holje, 1983 c). This was found to be independent of the radiation qualities studied here, which is in agreement with findings by Shuping and Judy (1977).

The relationship between sensitivity- and energy absorption characteristics is established (Holje, 1983 c). In this context attention is called to the fact that characterization of screen-film sensitivity in terms of reciprocal x-ray exposure, which is frequently seen, is confusing and may be misleading when interpreting the energy dependence of screen-film sensitivity.

#### 2.4 The light-yields of the screens

Indicators of the light-yields of the screens were determined (Holje, 1983 c). These are employed in a comprehensive demonstration of the relationship between light-yield, energy absorption and sensitivity of the screen-film systems. The balance between energy absorption and light-yield to attain a specific screen-film sensitivity is utilized for predictions of the ultimate image quality.

#### 2.5 The radiographic mottle; quantum mottle

The radiographic mottles of the screen-film systems were analyzed in detail (Holje, 1983 d). Determinations were made according to Swank (1973) of the noise-equivalent absorption in the screens. The investigation also included determinations of the noise-equivalent number of absorption events when the screens are exposed together with medium sensitive x-ray films. The inverses of these numbers are used for predictions of the quantum mottle. The radiographic mottle of the screen-film systems was evaluated by Wiener spectral analysis (Doi et al., 1982; Holje and Doi, 1982). A detailed analysis is performed of the correlation between predicted quantum mottle and measured radiographic mottle (Holje, 1983 d). In this analysis, special attention was paid to the screen structure mottle.

Evaluations were also performed of the influence of radiation quality on noise-equivalent absorption, predicted quantum mottle and measured radiographic mottle in the screen-film systems (Holje, 1983 d).

A comprehensive demonstration is made of the relationship between sensitivity, noise-equivalent absorption and quantum mottle in the screen-film systems (Holje, 1983 d). From this demonstration, it is possible to predict the increases in sensitivities that can be attained by use of new screen-film systems, provided that their quantum mottles are not allowed to be higher than those in conventional calcium tungstate systems.

## 2.6 The resolution capacity of the screen-film systems

The resolution capacities of the screen-film systems were evaluated in terms of their modulation transfer functions, MTFs, (Doi et al., 1982; Holje and Doi, 1982). A comprehensive demonstration is made of the relationship between sensitivity and resolution of the screen-film systems. This demonstration reveals the increases in sensitivities that can be attained by use of new screen-film systems with resolution capacities equal to those of conventional calcium tungstate systems.

## 2.7 Sensitivity, quantum mottle and resolution

A unique demonstration, which has been attempted in a previous study (Holje et al., 1977), of the correlation between sensitivity, noise and resolution properties of the screen-film systems is made (Holje and Doi, 1982). In this demonstration, the intensifying screens are assumed to be combined with films of such sensitivities that all screen-film systems contain the same low-frequency noise and predicted quantum mottle as those of a conventional calcium tungstate system. Since the Wiener spectrum of quantum mottle, and also the predicted quantum mottle, can be considered to be directly proportional to the sensitivity of the film, the sensitivities of the screen-film systems under such equal noise conditions are easily obtained (Holje and Doi, 1982, Equations 16, 17; Holje, 1983 d, Equation 13). The relationship between the sensitivity and the resolution properties of the screen-film systems under equal noise conditions reveals the potential advantages of the new intensifying screens.

### 3. RESULTS AND DISCUSSION

A previous investigation (Holje et al., 1977) has concluded that the M.R. screens, Blue Max screens and SE screens are essentially the same screens marketed under different names. This conclusion was based on the fact that the attenuation, sensitivity and resolution properties of the M.R. 200, Blue Max 1 and SE 2 screens were the same. Similar results were obtained for M.R. 400, Blue Max 2 and SE 4, as well as for M.R. 600 and SE 6 screens. For this reason, and since these screens have been modified, the physical properties were evaluated only for the M.R. screens. For practical purposes, the M.R. 200 data are expected to be applicable for the Blue Max 1 and SE 2 screens, the M.R. 400 data to be valid for the Blue Max 2 and SE 4 screens, and the M.R. 600 data to be valid for the SE 6 screens.

Due to the large number of screens incorporated in the study, their physical properties are presented in a concise, but still comprehensive, way. Absolute values are given at only one radiation quality, namely at that produced at 80 kV filtered with 20 mm aluminium. This radiation quality was chosen since the  $HVL_X$  of the radiation behind 20 mm aluminium is the same as that behind 25 cm of tissue, i.e. water, at 80 kV x-ray tube potential (Mika and Reiss, 1973). The influence of the radiation quality on the physical properties of all screen-film systems, with fluorescent layers of the same chemical composition, are treated jointly and presented as normalized to those at the radiation quality at 80 kV filtered with 20 mm aluminium. Absolute values of the physical properties of all screen-film systems are hereby easily derived at the various radiation qualities.

#### 3.1 The energy absorption in the screens

The energy absorption in the various intensifying screens is presented in Column 1 of Table 2. It is quite obvious that the new screens absorb more x-ray energy than the two calcium tungstate screens incorporated in the study. A presentation of the energy absorption in the intensifying screens versus their thickness (Holje, 1983 b, Figure 8) reveals that the

TABLE 2

Physical properties of the intensifying screens at 80 kV and 20 mm Al

| Intensifying screens | Energy absorp. | <u>Energy abs;K x-rays</u><br>Total energy absorp. | <u>Sensitivity</u><br>keV·mm <sup>2</sup> ×10 <sup>-7</sup> | Noise equiv.<br>absorp. |
|----------------------|----------------|----------------------------------------------------|-------------------------------------------------------------|-------------------------|
| M.R. 50              | 0.26           | 0.21                                               | 0.58                                                        | 0.35                    |
| M.R. 200             | 0.31           | 0.23                                               | 1.51                                                        | 0.43                    |
| M.R. 400             | 0.28           | 0.22                                               | 3.10                                                        | 0.39                    |
| M.R. 600             | 0.43           | 0.26                                               | 4.85                                                        | 0.60                    |
| SE 2                 | see M.R. 200   |                                                    | see M.R. 200                                                |                         |
| SE 4                 | see M.R. 400   |                                                    | see M.R. 400                                                |                         |
| SE 6                 | see M.R. 600   |                                                    | see M.R. 600                                                |                         |
| Blue Max 1           | see M.R. 200   |                                                    | see M.R. 200                                                |                         |
| Blue Max 2           | see M.R. 400   |                                                    | see M.R. 400                                                |                         |
| Rare Earth           | 0.38           | 0.25                                               | 3.84                                                        | 0.53                    |
| Titan 923            | 0.29           | 0.22                                               | 3.86                                                        | 0.40                    |
| Cronex Quanta II     | 0.31           | 0.24                                               | 3.41                                                        | 0.46                    |
| Type 4360            | 0.26           | 0.22                                               | 2.10                                                        | 0.38                    |
| Type 6359            | 0.34           | 0.25                                               | 2.89                                                        | 0.50                    |
| X-Omatic Reg.        | 0.35           | 0.24                                               | 1.45                                                        | 0.49                    |
| Cronex Par Sp.       | 0.15           | 0.032                                              | 0.65                                                        | 0.17                    |
| Rubin Super          | 0.18           | 0.037                                              | 0.14                                                        | 0.20                    |
| Grenex G-4           | 0.31           | 0.23                                               | 1.75                                                        | 0.41                    |
| Grenex G-8           | 0.39           | 0.25                                               | 3.91                                                        | 0.51                    |
| Lanex Fine           | 0.27           | 0.21                                               | 1.18                                                        | 0.35                    |
| Lanex Reg.           | 0.47           | 0.26                                               | 4.55                                                        | 0.60                    |
| Trimax Alpha 4       | 0.24           | 0.20                                               | 1.80                                                        | 0.32                    |
| Trimax Alpha 8       | 0.39           | 0.25                                               | 3.75                                                        | 0.52                    |
| Rarex BG Det.        | 0.28           | 0.18                                               | 1.34                                                        | 0.35                    |
| Rarex BG Mid Sp.     | 0.41           | 0.24                                               | 2.56                                                        | 0.52                    |
| Rarex BG High Sp.    | 0.50           | 0.26                                               | 4.43                                                        | 0.63                    |
| Rarex B Mid Sp.      | 0.27           | 0.13                                               | 3.48                                                        | 0.36                    |



energy absorption in the new screens may exceed that of calcium tungstate screens of equivalent thickness by as much as a factor of 1.6. Figure 1 illustrates the favourable energy absorption properties that exist in most of the new phosphor screens. Here the weighted mass energy absorption coefficients of the various intensifying screens (Holje, 1983 b, Section 3.3) are plotted versus their thicknesses. The decreases in mass attenuation coefficients with increasing screen thickness are assumed to be due to a filtering effect by the screens of the broad x-ray distribution passing through the screens. This presentation shows that the mass energy absorption coefficients of most of the new screens with barium, lanthanum or gadolinium as high Z-element are 1.6 to 1.8 times higher than those of the calcium tungstate screens.

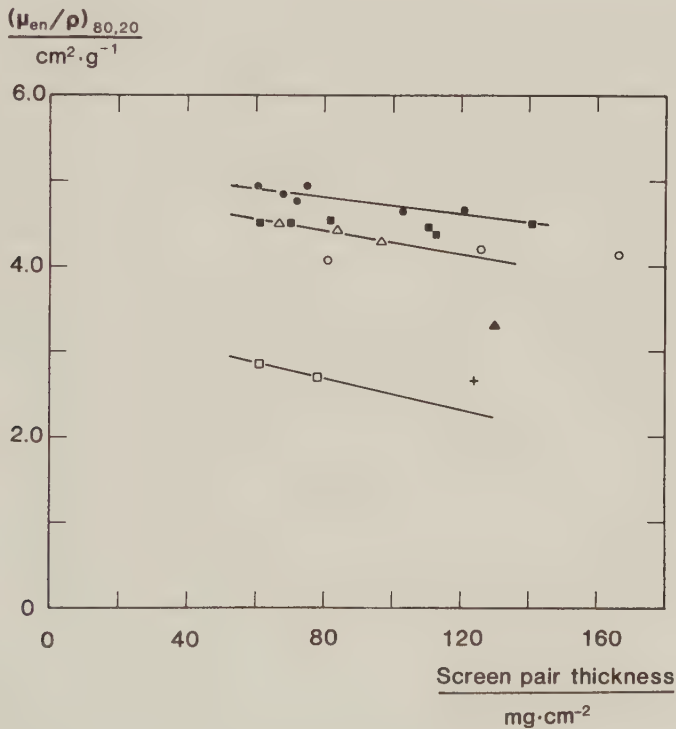


Figure 1. Weighted mass energy absorption coefficients of the phosphor screens at 80 kV filtered with 20 mm aluminium versus their thicknesses. + —  $\text{Y}_2\text{O}_2\text{S}$ -screens,  $\Delta$  —  $\text{BaFCl}$ -screens,  $\blacktriangle$  —  $\text{BaSO}_4/\text{SrSO}_4$ -screens,  $\bullet$  —  $\text{LaOBr}$ -screens  $\blacksquare$  —  $\text{Gd}_2\text{O}_2\text{S}$ -screens, o —  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ -screens,  $\square$  —  $\text{CaWO}_4$ -screens. The lines are fitted by linear regression analysis to the values for  $\text{LaOBr}$ -screens,  $\text{BaFCl}$ -screens and  $\text{CaWO}_4$ -screens, respectively.

The K x-ray absorption. The high frequency of K-shell interactions in the new screens leads to high production and also high absorption of K x-rays in these screens. This is shown in Column 2 of Table 2, where values are given on the contribution of K x-ray energy to the total energy absorption in the screens. Absorbed K x-ray energy amounts to less than 4 % of the total energy absorption in the calcium tungstate screens, but to between 13 % and 26 % in the new screens. The low values in the former screens is mainly due to the fact that very few photons in an 80 kV bremsstrahlung distribution have energies exceeding that of the K-absorption edge of tungsten, and consequently very few K x-rays are produced. The considerable contribution of K x-ray energy to the energy absorbed in screens made of new phosphors may come as a surprise to those used to working with conventional calcium tungstate systems. In spite of their unfavourable influence, the resolution capacities of the new screen-film systems are by far superior to those of conventional calcium tungstate systems with comparable sensitivity, see Figure 4. To exactly reveal the influence of K x-ray absorption on sensitivity versus resolution properties of screen-film systems, further investigations have to be performed. Since the variation with radiation quality of the K x-ray contribution to the total energy absorbed is quite different in screens with different chemical composition (Holje 1983 b, Section 3.6) one can anticipate that their resolution properties will respond in different ways to changes in radiation quality. It is, therefore, of decisive importance for the selection of appropriate screen-film system in different x-ray examinations, that their physical properties are compared at relevant radiation qualities. Although it may seem quite obvious to anyone, who is familiar with image quality and patient dose studies, that physical properties, evaluated with the intension of selecting an appropriate screen-film system for lung examinations, can not be applied for selection of an appropriate screen-film system for mammography examinations, it is surprisingly frequent that the influence of radiation quality on the physical properties is disregarded.

### 3.2 The sensitivity of the screen-film systems

The sensitivity of the screen-film systems is presented in Column 3 of

Table 2. From this it is obvious that the sensitivity of new screen-film systems may be as much as 7.5 times higher than that of the medium-sensitive calcium tungstate system Cronex Par Speed. It will be seen that the sensitivity increases attained with many of the new systems are achieved partly by increased energy absorption and partly by increased light-yield.

### 3.3 The relationship between sensitivity and energy absorption characteristics.

Since the energy deposited per unit screen area for production of a film density of 1.0 was found to be independent of the incident radiation qualities (Holje, 1983 c, Section 3.2) a simple relationship was derived between the sensitivity and energy absorption properties of the screen-film systems. The sensitivity characteristics were hereby shown to be directly related to the energy absorption properties of the screens (Holje, 1983 c, Equation 5). This relationship was also established experimentally; measured sensitivities of the screen-film systems were shown to vary with radiation quality in accordance with the variations of the energy absorption in the screens. This is shown in Figure 2.

Image contrast; its dependence on the chemical composition of the screen phosphor and choices of x-ray tube potential. Figure 2 shows, in an illustrative way, that screen-film systems of different phosphor materials have different sensitivity characteristics. Since a system's sensitivity characteristic affects the final image contrast, it is an important screen-film property. The differences in sensitivity characteristics between systems of different phosphor materials will lead to different image contrasts. Yttrium oxysulphide systems and calcium tungstate systems have relatively high sensitivity to low filtered x-ray beams, or, which is equivalent, to low energetic radiation. This implies that, if primary radiation only were to produce light exposing the film, these screen-film systems would give high contrast images. The presence of scattered radiation emanating from the objects, however, could produce the opposite results, since these screens also have high sensitivity to this low energetic radiation. Gadolinium oxysulphide systems, with their relatively low sensitivity to low filtered x-ray beams, i.e. low energetic radiation,

Relative sensitivity,  $S_{Rel.}$  (%)

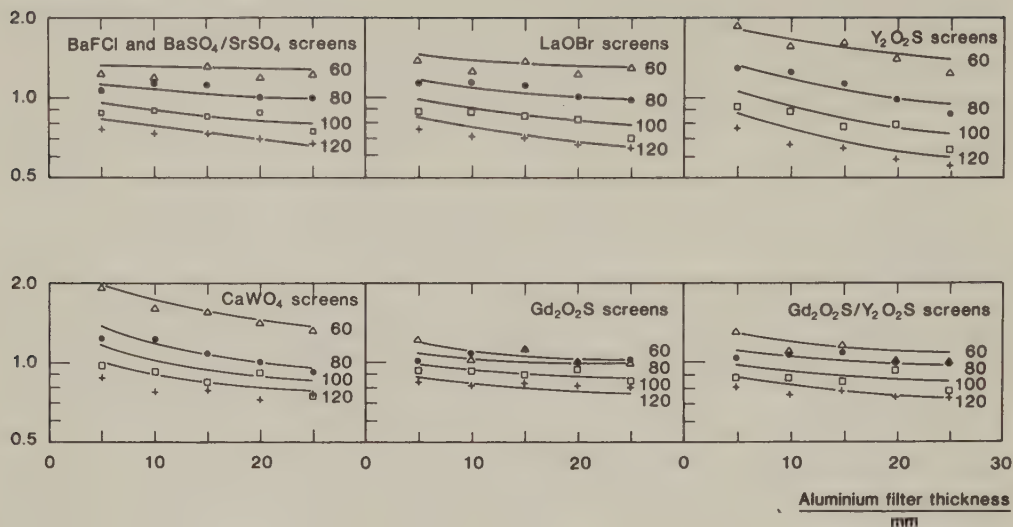


Figure 2. Sensitivity and energy absorption of the screen-film systems at various radiation qualities relative to those at 80 kV filtered with 20 mm aluminium. Measured sensitivities are indicated by symbols and energy absorptions by solid lines.  $\Delta$  — 60 kV,  $\bullet$  — 80 kV,  $\square$  — 100 kV and  $+$  — 120 kV x-ray tube potential.

can be expected to produce images with relatively low contrast, when primary radiation only exposes the systems. Due to their low sensitivity to low energetic radiation, the contrast reduction in these systems in the presence of scattered radiation will, however, not be as high as that in yttrium oxysulphide or calcium tungstate systems. Since the ratio of scattered-to-primary radiation is influenced by many factors, such as object thickness, field size, grid ratio, high tension, filter, geometry, etc., it is almost impossible to predict whether yttrium oxysulphide- and calcium tungstate systems or gadolinium oxysulphide systems would provide the greater contrast in clinical situations. It may well be that screen-film systems of a specific phosphor material give the highest contrast images in one clinical situation, but not in another. In spite of the fact that yttrium oxysulphide and calcium tungstate provide high contrast images in the absence of scattered radiation, their high sensitivity to low energetic radiation is a serious drawback. Since scattered radiation



does not transfer any diagnostic information, but only degrades the image quality, the ideal recording system would be a system which is sensitive only to transmitted primary radiation and not to scattered radiation. With this aspect laid on an ideal system, screens made of gadolinium oxysulphide would be preferred, and in situations where their image contrast is not high enough, improvements in contrast of the x-ray pattern can be done by using lower x-ray tube potential.

The choice of x-ray tube potential to obtain appropriate image contrast in different diagnostic examinations has been established during the years when calcium tungstate was used almost exclusively as the phosphor material of intensifying screens. The differences in energy responses of various phosphor materials, shown in Figure 2, however, indicate that one specific tube potential may not give the same contrast with screens made of different phosphors. When switching from conventional calcium tungstate systems to new screen-film systems, one has to be aware of the fact that it might be necessary to make changes in tube potential to maintain the image contrast. It was mentioned previously that the image contrast is heavily affected by the ratio of primary-to-scattered radiation. Since this may differ drastically between different radiological examinations, patient thicknesses and types of equipment, it is very difficult to theoretically predict the image contrast in individual situations. It is, therefore, easiest to analyse the image contrast in the practical situation. Too low image contrast should then be compensated for by a decrease of the x-ray tube potential and too high contrast by an increase of the tube potential. - Some of the confusion, which arose when the new screens were introduced, was certainly caused by their different energy dependence, which resulted in image contrasts, different from those obtained with calcium tungstate systems.

Adjustments of x-ray exposure to obtain correct film density. Adjustments of the x-ray exposure have to be made to obtain correct film density. In practical clinical work, these adjustments are made by changes in exposure time, tube current and/or tube potential. Due to differences in sensitivity characteristics, however, adjustments in x-ray tube potential

may not give the same change in the film's density when it is combined with screens made of different phosphor materials. X-ray exposure tables, a so-called point system, have been developed (Schwarz, 1961) for calcium tungstate systems and x-ray generators are available where adjustments in exposure time, tube current and tube potential are made in steps of one point, based on this system. Since calcium tungstate was the commonly used phosphor material in the past, there was no obvious reason for any separate analysis of the x-ray tube out-put and energy response of the screen-film systems. When the new screen-film systems were introduced, problems arose, however, since most users were not aware of their different energy response and its effect on the film density. Complaints came, saying that some of the new systems were too sensitive to exposure changes and that films came out either over- or under-exposed. (In extreme cases it was concluded that the new systems could not be used in diagnostic radiology!) Unfortunately sufficient information about the characteristics of the new systems was not available at the time when they were introduced. Many mistakes, which gave rise to unnecessary patient exposure, would have been avoided if data like those presented in Figure 2 had been available. It is now quite obvious that the differences in sensitivity characteristics of screen-film systems of different chemical compositions must be taken into account when the x-ray exposures are made. When small adjustments of the x-ray exposure have to be made to obtain correct film density, these should be made by adjustments of the x-ray tube current and/or the exposure time. Adjustments of the x-ray tube potential should be avoided, since they may not give the expected change in film density, which in turn results in re-takes and unnecessary exposure to the patient.

### 3.4 The light-yield of the screen-film systems.

Indicators of the light-yield of the screen-film systems were determined using the energy deposited per unit screen area as input signal and a certain film density as output signal (Holje, 1983 c, Section 3.4). Since all films were exposed to the same film density, the light-yield was obtained simply as the reciprocal of the energy deposited per unit screen area. It was shown that only one of the new screen-film systems, namely

M.R. 50, has lower light-yield than the medium-sensitive calcium tungstate system Cronex Par Speed. It was also shown that the light-yield of one of the new high sensitive systems, Titan 923, is more than three times higher than that of the Cronex Par Speed system.

### 3.5 Sensitivity; the balance between energy absorption and light-yield.

The energy absorption and the light-yield are important characteristics which, together with the sensitivity of the film, determine the final sensitivity of the screen-film system. Figure 3 presents a comprehensive demonstration of the relationship between the relative light-yield, energy absorption and sensitivity of all of the screen-film systems investigated. The three diagonal lines in Figure 3 indicate 12,5 %, 25 % and 50 % energy absorption. This parameter is of special interest, since it represents a physical property of the phosphors alone, whereas the relative light-yield (as it is quantified here), as well as the sensitivity, also include the sensitivities of the films. If the screens, therefore, are combined with films of other sensitivities, the relative light-yield and the sensitivity will change, while the energy absorption of course remains the same. This results in a shift of the data points which is parallel to the dotted diagonal lines.

Figure 3 shows that the screen-film system with the highest sensitivity, the lanthanum oxybromide system, M.R. 600, has more than seven times higher sensitivity than the Par Speed calcium tungstate system. It is evident from this illustration, that this increase in sensitivity has been attained partly by increased energy absorption and partly by increased relative light-yield. In addition, it should be noted that the magnitude of these increases of energy absorption and light-yield are almost equal. A solid line connects the Par Speed calcium tungstate system and this highly sensitive lanthanum oxybromide system. Below this, a parallel solid line is shown, originating at the gadolinium oxysulphide system Lanex Fine. These lines indicate two cases where sensitivity increases are achieved with equal fractional increases of energy absorption and light-yield. It is very interesting to see that many of the screen-film systems are located along either of these two lines.

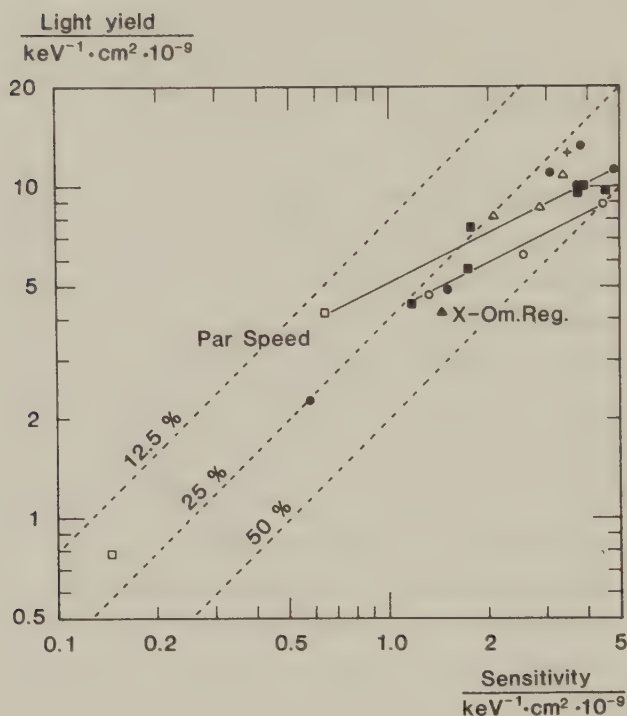


Figure 3. Sensitivity, light-yield and energy absorption of the screen-film systems at 80 kV filtered with 20 mm aluminium. The energy absorption is indicated by dotted lines. + —  $\text{Y}_2\text{O}_3$ -screens,  $\Delta$  —  $\text{BaFCl}$ -screens,  $\blacktriangle$  —  $\text{BaSO}_4/\text{SrSO}_4$ -screens,  $\bullet$  —  $\text{LaOBr}$ -screens,  $\blacksquare$  —  $\text{Gd}_2\text{O}_3$ -screens,  $\circ$  —  $\text{Gd}_2\text{O}_3/\text{Y}_2\text{O}_3$ -screens and  $\square$  —  $\text{CaWO}_4$ -screens.

The balance between energy absorption and light-yield to obtain a specific sensitivity is important, since it affects the ultimate image quality. High light-yield leads to low absorbed x-ray energy, i.e. few x-ray quanta are utilized for production of the film density. This will result in high quantum mottle. If the high light-yield is related to large light diffusion, the resolution will be low. If, on the other hand, high energy absorption is adopted, numerous x-ray quanta are utilized for the production of the film density. This results in low quantum mottle. If the high energy absorption is attained by the use of thick screens, light-diffusion will be large, which again will result in low resolution capacity.



As far as screens with equal phosphor layers are concerned, one can expect that sensitivity gains, by means of enhancements of both energy absorption and light-yield, will involve impairment of the resolution as well as of the noise properties of the screen-film systems. A moderate impairment of these two properties can be expected to be less destructive to the overall image quality than would be the case if a drastic reduction was made of only one of them, while the other was kept constant. The fact that so many systems in Figure 3 are located along the two solid diagonal lines, indicating equal increases of energy absorption and light-yield to obtain a sensitivity gain, can be considered as evidence, that this also is the case when put into practice.

### 3.6 The noise-equivalent absorption in the intensifying screens.

The noise-equivalent absorption in the intensifying screens is presented in Column 4 of Table 2. It is obvious that all new intensifying screens have higher noise-equivalent absorptions than the calcium tungstate systems incorporated in the study. This has been shown to be a combined effect of the high energy absorption and the low mean energy of the energy deposition events, i.e. mean energy deposition, in these screens (Holje, 1983 d, Section 3.2). The mean energy deposition, which is determined by the energy absorption characteristics of the screens, was found to be lower in all new intensifying screens than that in conventional calcium tungstate screens (Holje, 1983 d, Section 3.1). This means that a larger number of absorption events have to take place in the new screens to attain absorbed energy equal to that in calcium tungstate screens. This property of the new screens is important, since it reduces the appearance of quantum mottle in the final images. A presentation of the noise-equivalent absorptions in the screens versus their thicknesses (Holje, 1983 d, Figure 3) reveals that the noise-equivalent absorptions in the new screens may exceed those of calcium tungstate screens of equal thickness by as much as a factor of 2. It is therefore obvious that these screens must have a much higher potential than the calcium tungstate screens to produce images with low quantum mottle.

The influence of radiation quality on the noise-equivalent absorption was shown to be quite different in screens made of different phosphors (Holje, 1983 d, Section 3.3). The importance of specifying radiation quality when comparing noise-equivalent absorption was obvious, since screen pairs with equal noise-equivalent absorption at one radiation quality may differ quite drastically, when exposed to another radiation quality. Although equal at one radiation quality, a difference of a factor of 2.5 at the extreme may be found at another radiation quality between the noise-equivalent absorption in two screen pairs made of yttrium oxysulphide and gadolinium oxysulphide.

### 3.7 Measured radiographic mottle versus predicted quantum mottle.

The noise-equivalent number of absorption events in the screen-film systems was determined (Holje 1983 d, Section 3.4). The inverses of these numbers, which are presented in Table 3, Column 1, were used for predictions of the quantum mottle in the screen-film systems. These predictions are expected to be rather accurate, since good agreement was found between predicted quantum mottle and measured radiographic mottle at low frequencies, see Column 2 of Table 3, when the existence of screen structure mottle was taken into account (Holje 1983 d, Section 3.4). Since the structure mottles in some screens might be of the order of the quantum mottle, the inverse of the noise-equivalent number of absorption events may be a better indicator of the relative quantum mottle in screen-film systems than the measured radiographic mottle, which also includes the structure mottle.

The influence of radiation quality on the quantum mottle in the screen-film systems was evaluated. Good agreement was found between the variations with radiation quality of measured radiographic mottle and predicted quantum mottle (Holje, 1983 d, Section 3.5). The quantum mottle in gadolinium oxysulphide systems is very little affected by the radiation qualities used here. Since this is the case also for their variation in attenuation, energy absorption, sensitivity and noise-equivalent absorption, it is quite evident that these systems are outstanding in their constancy of physical properties when they are exposed to various

TABLE 3

Physical properties of the intensifying screens at 80 kV and 20 mm AL

| Intensifying<br>screens | $\frac{1/Nq}{\text{mm}^2 \times 10^{-5}}$ | $\frac{WS(0.1 \text{ c/mm})}{\text{mm}^2 \times 10^{-4}}$ | Rel.sens.at<br>equal q.mottle | MTF(2 c/mm)* |
|-------------------------|-------------------------------------------|-----------------------------------------------------------|-------------------------------|--------------|
| M.R. 50                 | 0.93                                      | 1.47                                                      | 2.06                          | 0.570        |
| M.R. 200                | 1.00                                      | 2.20                                                      | 2.53                          | 0.342        |
| M.R. 400                | 4.55                                      | 4.30                                                      | 2.29                          | 0.304        |
| M.R. 600                | 4.61                                      | 3.90                                                      | 3.53                          | 0.202        |
| SE 2                    | see M.R. 200                              |                                                           | see M.R. 200                  |              |
| SE 4                    | see M.R. 400                              |                                                           | see M.R. 400                  |              |
| SE 6                    | see M.R. 600                              |                                                           | see M.R. 600                  |              |
| Blue Max 1              | see M.R. 200                              |                                                           | see M.R. 200                  |              |
| Blue Max 2              | see M.R. 400                              |                                                           | see M.R. 400                  |              |
| Rare Earth              | 4.14                                      | 2.90                                                      | 3.12                          | 0.270        |
| Titan 923               | 5.50                                      | 4.19                                                      | 2.35                          | 0.190        |
| Cronex Quanta II        | 4.20                                      | 3.75                                                      | 2.71                          | 0.218        |
| Type 4360               | 3.14                                      | 4.13                                                      | 2.24                          | 0.391        |
| Type 6359               | 3.30                                      | 4.05                                                      | 2.94                          | 0.317        |
| X-Omatic Reg.           | 1.67                                      | 1.81                                                      | 2.88                          | 0.364        |
| Cronex Par Sp.          | 2.19                                      | 2.51                                                      | 1.00                          | 0.346        |
| Rubin Super             | 0.41                                      | 1.22                                                      | 1.18                          | 0.625        |
| Grenex G-4              | 2.45                                      | 1.89                                                      | 2.41                          | 0.376        |
| Grenex G-8              | 4.31                                      | 2.53                                                      | 3.00                          | 0.279        |
| Lanex Fine              | 1.90                                      | 1.70                                                      | 2.06                          | 0.510        |
| Lanex Reg.              | 4.31                                      | 2.30                                                      | 3.53                          | 0.241        |
| Trimax Alpha 4          | 3.22                                      | 2.04                                                      | 1.88                          | 0.385        |
| Trimax Alpha 8          | 4.13                                      | 2.50                                                      | 3.06                          | 0.222        |
| Rarex BG Det.           | 2.18                                      | 1.42                                                      | 2.06                          | 0.421        |
| Rarex BG Mid Sp.        | 2.78                                      | 2.18                                                      | 3.06                          | 0.271        |
| Rarex BG High Sp.       | 3.99                                      | 2.08                                                      | 3.71                          | 0.151        |
| Rarex B Mid Sp.         | 5.47                                      | 3.80                                                      | 2.12                          | 0.225        |

\* evaluated at 80 kV and 1.64 mm aluminium filter.

radiation qualities. The variation with radiation quality of the quantum mottle in yttrium oxysulphide systems is comparatively large. This also applies to their variation in other physical properties. The quantum mottle in systems made of lanthanum oxybromide, barium fluorochloride, barium sulphate/strontium sulphate and calcium tungstate adopt an intermediate position regarding its variation with radiation quality. This is also the case for other physical properties of these screen-film systems.

The significance of variations in quantum mottle in clinical examinations has not been investigated. One would expect, however, that preference would be given to systems which do not change image quality drastically with the incident radiation quality. The use of gadolinium oxysulphide screens should, therefore, cause less disturbance in clinical work, since they do not introduce any drastic variations in quantum mottle depending on the radiological examination being performed.

### 3.8 Sensitivity, noise-equivalent absorption and quantum mottle.

Due to their high noise-equivalent absorption, the new screens should be expected to produce images with less quantum mottle than those produced in calcium tungstate systems. The quantum mottle, however, is also influenced by the light-yield of the screens and the sensitivity of the film. Systems with screens with high light-yield and/or films with high sensitivity provide little absorbed energy, few absorption events and, thus, high quantum mottle. In the light of their favourable absorption characteristics, it may be seen that problems with high quantum mottle should never arise in the new screen-film systems. These came, however, as a consequence of the desire to utilize the high conversion efficiency of the new phosphors. The sensitivity of the screen-film systems could thereby be increased, which in turn provides decreased patient doses.

In spite of their high noise-equivalent absorption, the noise-equivalent number of absorption events in only five new screen-film systems exceed that in the medium sensitive calcium tungstate system Cronex Par Speed. The quantum mottle can consequently in only these five systems be expected to be lower than that in the Cronex Par Speed system, see Table 3,



Column 1. A comparison of the quantum mottle in various screen-film systems, however, is significant only when this is correlated to their sensitivities.

Figure 4 provides a comprehensive presentation of the physical properties of sensitivity, noise-equivalent absorption and quantum mottle in the screen-film systems. There is a general tendency, seen in Figure 4, that high sensitivity of the screen-film systems results in high quantum mottle. The increase in sensitivity attained with the new systems compared to that of the calcium tungstate systems, however, is higher than the increase in their quantum mottle. This is a consequence of their higher noise-equivalent absorption. The most sensitive system, the lanthanum oxybromide system, M.R. 600, has more than seven times higher sensitivity than the Cronex Par Speed system of calcium tungstate. The increase in quantum mottle, however, is only slightly more than a factor of two. This discrepancy is due to the 3.5 times higher noise-equivalent absorption in the M.R. 600 screens.

The physical properties of the two systems Cronex Par Speed and X-Omatic Regular provide interesting comparisons. The sensitivity of the X-Omatic Regular system is more than twice as high as that of the Par Speed system. Its noise-equivalent absorption, however, is almost three times as high. This has as a consequence that the quantum mottle in the X-Omatic Regular system is lower than that in the Par Speed system by about 25 %.

Screen-film sensitivities at equal noise conditions. The noise-equivalent absorption,  $B_N$ , which is indicated by diagonal lines in Figure 4, is a parameter of specific interest, since it expresses an isolated property of the intensifying screens. The sensitivity, as well as the quantum mottle, are properties of the screens in combination with specific film types. If the intensifying screens are combined with films of other sensitivities, the data points in Figure 4 will shift parallel to the diagonal lines. It is, therefore, possible, through proper choices of films, to let all of the screen-film systems adopt the same quantum mottle as that in the Cronex Par Speed calcium tungstate system. The sensitivities of the screen-film systems, relative to that of the Cronex Par Speed

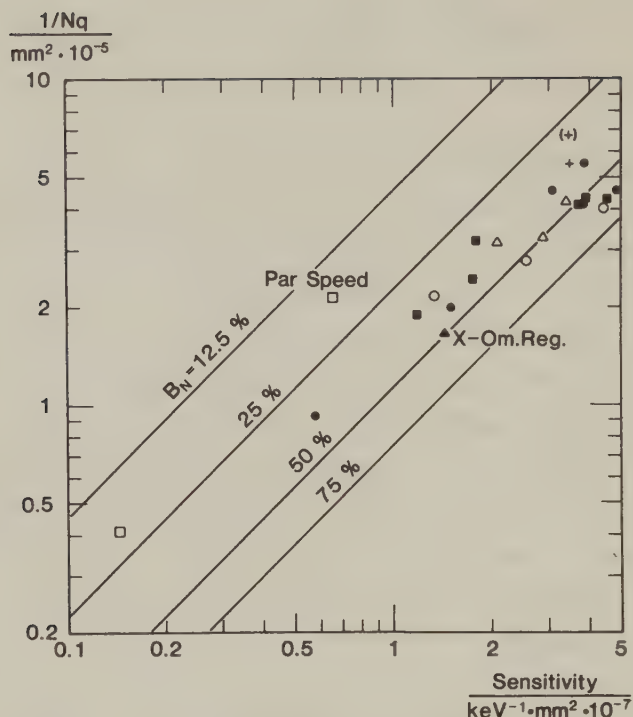


Figure 4. Sensitivity, noise-equivalent absorption and quantum mottle of the screen-film systems at 80 kV filtered with 20 mm aluminium.  $1/Nq$ , the inverse noise-equivalent number of absorption events, is an indicator of quantum mottle. The diagonal lines indicate noise-equivalent absorption. + —  $Y_2O_2S$ -screens,  $\Delta$  —  $BaFCl$ -screens,  $\blacktriangle$  —  $BaSO_4/SrSO_4$ -screens,  $\bullet$  —  $LaOBr$ -screens,  $\blacksquare$  —  $Gd_2O_2S$ -screens,  $o$  —  $Gd_2O_2S/Y_2O_2S$ -screens,  $\square$  —  $CaWO_4$ -screens.

system, at such "equal noise conditions" are shown in Column 3 of Table 3. The most sensitive system is the high-sensitive gadolinium oxysulphide/yttrium oxysulphide system, which under this condition provides a sensitivity gain by a factor of 3.7. This is thus the maximal sensitivity gain which can be attained with the new screen-film systems, provided that the quantum mottle is not allowed to increase. Due to their higher noise-equivalent absorption, all new screen-film systems will attain higher sensitivity than the Par Speed calcium tungstate system under equal noise conditions. The sensitivity gains, which vary between 1.9 and 3.7, are remarkable. Similar results are obtained when the noise properties are evaluated by means of Wiener spectral analysis (Holje and Doi, 1982).

### 3.9 The resolution properties of the screen-film systems.

To facilitate a comparison of the many systems investigated, their modulation transfer factors at 2 cycles per mm were chosen as an indicator of their resolution properties, see Column 4 of Table 3. The MTFs of screen-film systems included in this study very rarely intersect, and therefore the choice of another spatial frequency will provide very similar results in this comparison.

### 3.10 The relationship between resolution and sensitivity of the screen-film systems.

A comprehensive demonstration of the relationship between the resolution and sensitivity of the screen-film systems investigated is presented in Figure 5. Data on resolution and sensitivity of the two calcium tungstate systems Cronex Detail and Cronex Hi-Plus are included in this presentation (Holje and Doi, 1982). The wide scatter of data points indicates the complex relationship between these two physical properties, which is influenced by many factors, such as phosphor composition, screen thickness, particle size, and phosphor deposition density.

The two parallel diagonal lines indicate the general trend of an inverse relationship between resolution and sensitivity. The lower line goes through the data points for calcium-tungstate systems and the upper line goes through data points for high-sensitive, high-resolution systems based on new phosphors. The sensitivities of the systems, located along the upper line, are four times higher than those of calcium tungstate systems with comparable resolution capacity. Figure 5 shows that almost all new screen-film systems are between 1.5 and 4 times as sensitive as calcium tungstate systems of comparable resolution. If 20 percent loss of sensitivity is allowed for, because of the different energy dependance of the new systems (this is best illustrated in Figure 5, Holje 1983 c), the gain in sensitivity is reduced to 1.2 - 3.2 times, which is still very high for some systems.

In the determinations of the resolution properties of the screen-film systems it appeared that the film sensitivity does not have any signifi-

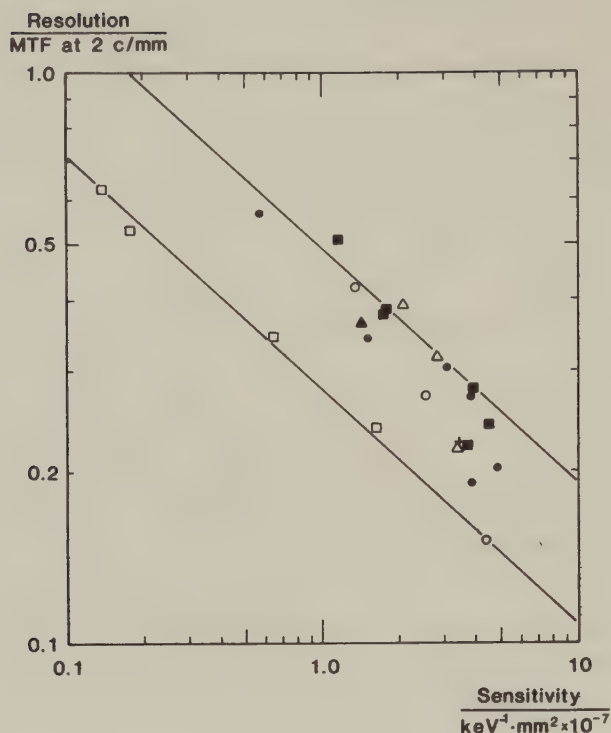


Figure 5. Relationship between resolution and sensitivity of the screen-film systems. + — Y<sub>2</sub>O<sub>3</sub>S-systems, Δ — BaFCl-systems, ▲ — BaSO<sub>4</sub>/SrSO<sub>4</sub>-systems, ● — LaOBr-systems, ■ — Gd<sub>2</sub>O<sub>3</sub>S-systems, o — Gd<sub>2</sub>O<sub>3</sub>S/Y<sub>2</sub>O<sub>3</sub>S-systems, □ — CaWO<sub>4</sub>-systems.

cant effect on their MTFs <sup>\*</sup>) (Holje and Doi, 1982). If the screens, therefore, are combined with films of other sensitivities, this will affect the screen-film sensitivities, while their resolutions will remain the same. This finding will be utilized in the following comprehensive comparison of the sensitivity, noise and resolution properties of the screen-film systems.

<sup>\*</sup>) Other factors such as the colour of the film base, which affects the crossover exposure, is, however, expected to have a considerable effect on the resolution properties.



The relationship between the resolutions and the screen-film sensitivities at equal noise conditions. A unique illustration of the physical properties, sensitivity, noise and resolution, of the screen-film systems is presented in Figure 6. The intensifying screens are here assumed

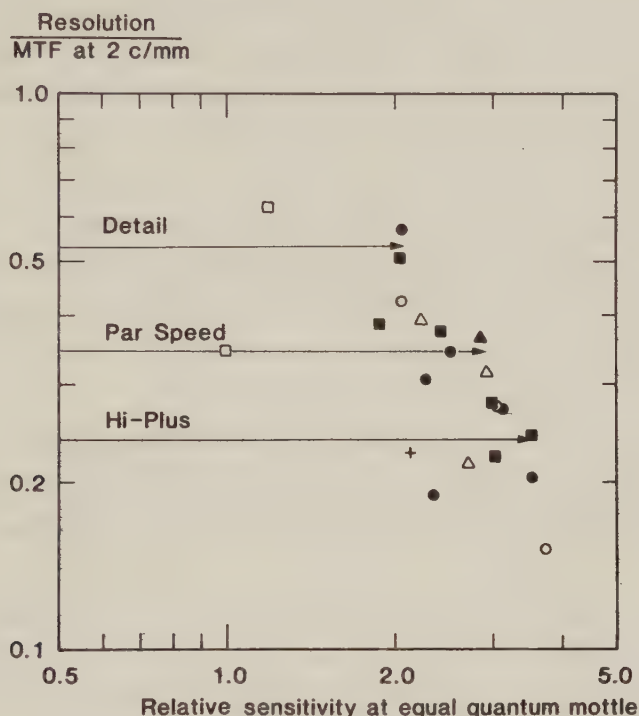


Figure 6. Relationship between resolution and sensitivity of the screen-film systems at equal noise conditions. The sensitivities are expressed relative to that of the Cronex Par Speed system. The resolution levels of the Cronex Detail, Par Speed and Hi-Plus systems are indicated. Maximal sensitivities of new screen-film systems with equivalent resolutions are indicated by arrows. + —  $\text{Y}_2\text{O}_3\text{S}$ -systems,  $\Delta$  —  $\text{BaFCl}$ -systems,  $\blacktriangle$  —  $\text{BaSO}_4/\text{SrSO}_4$ -systems,  $\bullet$  —  $\text{LaOBr}$ -systems,  $\blacksquare$  —  $\text{Gd}_2\text{O}_3\text{S}$ -systems,  $o$  —  $\text{Gd}_2\text{O}_3\text{S}/\text{Y}_2\text{O}_3\text{S}$ -systems,  $\square$  —  $\text{CaWO}_4$ -systems.

to be combined with films of such sensitivities that all screen-film systems have the same quantum mottle as that in the medium-sensitive calcium tungstate system Cronex Par Speed, see Section 3.8. The corresponding sensitivities of the screen-film systems, relative to that of the Cronex Par Speed system, are shown in Column 3 of Table 3. Figure 6 thus illustrates the relationship between resolution and sensitivity properties of the

screen-film systems at equal noise conditions. The potential advantages of the new intensifying screens are here clearly demonstrated.

The resolution levels, i.e. the MTFs at 2 cycles per mm, are indicated for the calcium tungstate systems Cronex Detail, Cronex Par Speed and Cronex Hi-plus at 0.530, 0.346 and 0.239 respectively (Holje and Doi, 1982, Table 2.3). The maximal sensitivities, which can be obtained with new screen-film systems with equivalent resolutions (and quantum mottles) are indicated by arrows. Figure 6 shows that

The resolution and noise properties of the Cronex Detail system can be maintained, or even improved, with new systems having approximately two times higher sensitivity than the "medium-sensitive" Cronex Par Speed system.

Imaging properties equal to, or better, than those of the Cronex Par Speed calcium tungstate system can be achieved with new systems having almost three times higher sensitivity.

An image quality corresponding to the Cronex Hi-Plus calcium tungstate system can be provided by new systems having 3.5 times higher sensitivity than the "medium-sensitive" Cronex Par Speed system.

#### 4. CONCLUSIONS

This evaluation of the physical properties of screen-film systems shows that

1. Gadolinium oxysulphide systems are outstanding in their constancy with variations in radiation quality of attenuation, energy absorption, sensitivity, noise-equivalent absorption and quantum mottle. Gadolinium oxysulphide systems also exhibit the lowest sensitivity to scattered radiation of all of the systems investigated, which is advantageous for the image

quality, i.e. the image contrast.

2. Some of the new systems exhibit a relatively high noise level when medium sensitive x-ray films are used. Provided that this high noise is due to quantum mottle, it can be reduced if films of lower sensitivities are used.
3. A considerable reduction in patient dose can be achieved without reduction of radiographic image quality, if the new screen-film systems are used in a proper way.

## 5. ACKNOWLEDGEMENTS

My most sincere thanks are due to

Emeritus Professor Kurt Lidén for his unfailing and kind support

Professor Kunio Doi for his support, advices and criticism and for his believe in my work

Professor Bertil Persson for his encouragement and enthusiasm for new projects

Dr. Thure Holm for his valuable support throughout the years

Claes Westrup for his indispensable help

All colleagues and friends at the Radiation Physics Department in Lund, at the Kurt Rossmann Laboratories in Chicago and at the Roentgen Department in Lund

All other friends, if I still have any, and

My family

Without your combined support, stimulation and friendship this work could not have been done

This work was in part supported by

The Swedish Institute for the Planning and Rationalization of Health and Social Welfare Services, and

U.S. Department of Health and Human Services, Bureau of Radiological Health



## REFERENCES

Arnold B.A. and Bjärngard B.E., 1979

The effect of phosphor K x-rays on the MTF of rare-earth screens  
Medical Physics 6(6):500-503

Barnard H.J., 1982

Image quality standards

Radiology 143:275-276

Bregulla W. and Schmidt T., 1981

Significance of rare-earth intensifying screens for dose reduction  
in x-ray diagnosis

Electromedica 4/81

Buchanan R.A., Finkelstein S.I. and Wickersheim K.A., 1972

X-ray exposure reduction using rare-earth oxysulphide intensifying  
screens

Radiology 105:185-190

Castle J.W., 1977

Sensitivity of radiographic screens to scattered radiation and its  
relationship to image contrast

Radiology 122:805-809

de Carvalho A. and Jörgensen J., 1978

Rare-earth and calcium tungstate intensifying screens, a comparative  
study of relative speed, radiation doses and resolving power

Fortschr. Röntgenstr. 128(3):358-363

Degenhardt H., 1980

On the use of rare-earth luminescent materials in high definition  
intensifying screens

Electromedica 3/80

Doi K. and Rossmann K., 1975

Measurements of optical and noise properties of screen-film systems in radiography

Medical x-ray Photo-Optical Systems Evaluation, SPIE Vol 56:45-53

Doi K., Rossmann K. and Haus A.G., 1977

Image quality and patient exposure in diagnostic radiology

Photographic Science and Engineering 21(5):269-277

Doi K., Holje G., Loo L-N, Chan H-P, Sandrik J.M., Jennings R.J. and Wagner R.F., 1982

MTF's and Wiener spectra of radiographic screen-film systems.

Part 1. Interlaboratory comparison of measurements

U.S. Department of Health and Human Services HHS Publication

FDA 82-8187, Bureau of Radiological Health, Rockville, Maryland 20857, U.S.A.

Goodman D.A., Wells C.A. and Weston P.J., 1977

An evaluation of some screen film combinations for use in radiography of the extremities

Radiography 43(515):253-255

Holje G., 1983 a

Photon attenuation by radiographic intensifying screens

CODEN Report LUNFD6 (NFRA-3033) / LUMEDW (MERI-3033), Dept. of Radiation Physics, Lund University, Lund, Sweden

Holje G., 1983 b

Energy absorption in radiographic intensifying screens

CODEN Report LUNFD6 (NFRA-3034) / LUMEDW (MERI-3034), Dept. of Radiation Physics, Lund University, Lund, Sweden

Holje G., 1983 c

Sensitivity characteristics of radiographic screen-film systems

CODEN Report LUNFD6 (NFRA-3035) / LUMEDW (MERI-3035), Dept. of Radiation Physics, Lund University, Lund, Sweden

Holje G., 1983 d

Radiographic mottle in screen-film systems used in diagnostic radiology

CODEN Report LUNFD6 (NFRA-3036) / LUMEDW (MERI-3036), Dept. of Radiation Physics, Lund University, Lund, Sweden

Holje G., 1983 e

Energy absorption of fluorescent K x-rays produced in the phosphor layers of radiographic intensifying screens

CODEN Report LUNFD6 (NFRA-3037) / LUMEDW (MERI-3037), Dept. of Radiation Physics, Lund University, Lund, Sweden

Holje G., 1983 f

Coefficients for converting x-ray exposure to photon fluence and energy fluence

CODEN Report LUNFD6 (NFRA-3038) / LUMEDW (MERI-3038), Dept. of Radiation Physics, Lund University, Lund, Sweden

Holje G., Svahn G., Hårdstedt C., Ramnhagen A., Öbergh A. and Forsberg H., 1977

Intensifying screens for x-ray cassettes, performance usability, etc  
(In Swedish, English summary)

The Swedish Institute for the Planning and Rationalization of Health and Social Welfare Services, Spri Report S 67

Holje G. and Doi K., 1982

MTF's and Wiener spectra of radiographic screen-film systems

Part 2. Sensitivity, sensitometry, resolution and noise characteristics of new screen-film systems

U.S. Department of Health and Human Services HHS Publication

FDA 82-8187, Bureau of Radiological Health, Rockville, Maryland 20857, U.S.A.

Hollins K.D., 1975

Rare-earth phosphor intensifying screens

Radiography 4(491):249-251

Karlsson M., Wickman G. and Hettinger G., 1977

Characteristics of x-ray screen phosphors at photon energies between 20-140 keV

Presented at the Ninth Nordic Meeting on Clinical Physics, Gothenburg, Sweden

Mika N. and Reiss K.H., 1973

Tabellen zur Röntgendiagnostik

Siemens Aktiengesellschaft, Bereich Medizinische Technik, Erlangen

Rao G.U.V., Fatouros P.P. and James A.E., 1978

Physical characteristics of modern radiographic screen-film systems

Investigative Radiology 13:460-469

Rossi R.P., Hendee W.R. and Ahrens C.R., 1976

An evaluation of rare-earth screen-film combinations

Radiology 121:465-471

Rossmann K., 1969

Image quality

Radiologic Clinics of North America VII(3):419-433



Rossmann K. and Doi K., 1975

Studies of screen-film optics, past present and future

Medical x-ray Photo-Optical Systems Evaluations, SPIE Vol 56:41-43

Shuping R.E. and Judy P.F., 1977

Energy absorbed in calcium tungstate x-ray screens

Medical Physics 4(3):239-243

Skucas J. and Gorski J., 1980

Application of modern intensifying screens in diagnostic radiology

Medical Radiography and Photography 56(2):25-35

Soila P., Edgren J., Landtman M. and Laasonen L., 1976

Test of rare earth oxysulphide intensifying screens

British Journal of Radiology 50:205-207

Stevens A.L.N., 1975

New phosphors for x-ray screens

Medicamundi 20/1:12-22

Stevens A.L.N. and Pingault F., 1975

$\text{BaFCl:Eu}^{2+}$ , A new phosphor for x-ray intensifying screens

Philips Research Reports 30:277-290

Swank R.K., 1973

Absorption and noise in x-ray phosphors

Journal of Applied Physics 44(9):4199-4203

Storm E. and Israel H.J., 1967

Photon cross sections from 0.001 to 100 MeV for elements 1 through 100  
(LA-3753, UC-34, Physics, TID-4500)

Los Alamos Scientific Laboratory of the University of California,  
Los Alamos, New Mexico, U.S.A.

Thompson T.T., Radford E.L. and Kirby C.C., 1977

A look at rare-earth and high speed intensifying screens

Applied Radiology, March-April:71-72, 129

Venema H.W., 1979

X-ray absorption, speed and luminescent efficiency of rare earth and other intensifying screens

Radiology 130:765-771

Vyborny C.J., Loo L-N and Doi K., 1982

The energy-dependent behaviour of noise Wiener spectra in their low-frequency limits: Comparison with simple theory

Radiology 44(3):619-622

Wagner R.F. and Weaver K.E., 1976

Prospects of x-ray exposure reduction using rare-earth intensifying screens

Radiology 118:183-188







Dokumentutgivare  
Inst för radiofysik  
Handläggare

Dokumentnamn  
CODEN Report  
Utgivningsdatum  
April 1983

Dokumentbeteckning  
3033  
Ärendebeteckning

Författare  
Gunnila Holje

Dokumenttitel och undertitel

PHOTON ATTENUATION BY RADIOGRAPHIC INTENSIFYING SCREENS

A study of attenuation by intensifying screens with fluorescent layers of various chemical compositions under exposure conditions simulating those occurring in various diagnostic X-ray examinations.

Referat (sammandrag)

The photon attenuation by intensifying screens of different chemical composition has been determined. The attenuation of photons between 20 keV and 120 keV was measured by use of a multi-channel analyzer and a broad bremsstrahlung distribution. The attenuation by the intensifying screens was hereby determined simultaneously at many different monoenergetic photon energies. Experimentally determined attenuations were found to agree well with attenuations calculated from mass attenuation coefficients. The attenuation by the screens was also determined at various bremsstrahlung distributions, simulating those occurring behind the patient in various diagnostic X-ray examinations. The high attenuations in some of the intensifying screens form the basis for an analysis of the construction of asymmetric screen pairs. Single screen systems are suggested as a favourable alternative to thick screen pair systems.

Referat skrivet av

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Indextermer (ange källa)

Omfång Övriga bibliografiska uppgifter

Språk

Sekretessuppgifter

ISSN

ISSN

Dokumentet kan erhållas från

Mottagarens uppgifter

Inst för radiofysik vid Lunds universitet  
Lasarettet  
S-221 85 LUND

Fria

SIS-  
OE1

DOKUMENTDATATABLAD enligt SIS 82 10 12

Blankett LU 11:25 1976-07



# PHOTON ATTENUATION BY RADIOGRAPHIC INTENSIFYING SCREENS

A study of attenuation by intensifying screens with fluorescent layers of various chemical compositions under exposure conditions, simulating those occurring in various diagnostic x-ray examinations

Gunnila Holje

Lund 1983



## CONTENTS.

|                                                                                           | Page |
|-------------------------------------------------------------------------------------------|------|
| 1. INTRODUCTION.....                                                                      | 1    |
| 2. MEASUREMENTS AND CALCULATIONS OF THE ATTENUATION.....                                  | 4    |
| 2.1 The detector and radiation source                                                     | 4    |
| 2.2 The geometry of the experimental set-up                                               | 4    |
| 2.3 Attenuation measurements at photon energies between<br>20 keV and 120 keV             | 5    |
| 2.4 Attenuation measurements at discrete photon energies                                  | 6    |
| 2.5 Attenuation determined from mass attenuation<br>coefficients of the phosphors         | 8    |
| 2.6 Attenuation of x-ray distributions                                                    | 9    |
| 2.7 Determinations of the screen thicknesses                                              | 10   |
| 2.8 Asymmetric screen pairs; a theoretical consideration<br>using monoenergetic radiation | 10   |
| 3. RESULTS AND DISCUSSION.....                                                            | 13   |
| 3.1 The attenuation at photon energies between 10 keV<br>and 120 keV                      | 13   |
| * Yttrium screens                                                                         | 15   |
| * Barium screens                                                                          | 15   |
| * Lanthanum screens                                                                       | 16   |
| * Gadolinium screens                                                                      | 16   |
| * Gadolinium/Yttrium screens                                                              | 17   |
| * Tungstate screens                                                                       | 17   |
| 3.2 The photon attenuation at 80 kV and 20 mm aluminium<br>filter                         | 17   |
| 3.3 The attenuation of x-ray distributions                                                | 21   |
| * Yttrium screens                                                                         | 22   |
| * Barium and Lanthanum screens                                                            | 23   |
| * Gadolinium screens                                                                      | 23   |
| * Gadolinium/Yttrium screens                                                              | 24   |
| * Tungstate screens                                                                       | 25   |

(cont.)



|                 |                                     |    |
|-----------------|-------------------------------------|----|
| 3.4             | Screen thicknesses                  | 25 |
| 3.5             | Asymmetric screen pairs             | 27 |
|                 | * The effect of x-ray distributions | 27 |
|                 | * Measured data                     | 27 |
|                 | * The effect of light absorption    | 29 |
| REFERENCES..... |                                     | 30 |

## 1. INTRODUCTION

The ability of the phosphor material to interact with incident photons is of fundamental importance for the performance of the screens. High interaction frequency is usually coupled to high absorption of photon energy in the screens, which is advantageous for the screen-film sensitivity (Buchanan et al., 1972). Through improved energy absorption, screen-film sensitivity can be improved without any increase of screen thickness. This is important, since thick screens have less ability to provide high resolution. Also the quantum mottle is coupled to the energy absorption of the screens. Screens with high energy absorption and low light-yield have a high capacity for providing images with low quantum mottle (Wagner and Weaver, 1976; Holje, 1983 d).

Buchanan et al. (1972) showed that  $\text{La}_2\text{O}_2\text{S}$ - and  $\text{Gd}_2\text{O}_2\text{S}$ -screens have higher x-ray energy absorption than the conventional  $\text{CaWO}_4$ -screens in the energy range of interest in diagnostic radiology. Although certain confusion exists in the terminology, these determinations seem to be based on the attenuation by the screens, which, at least as a first order approximation, provides a useful indicator of their energy absorption.

X-ray stopping power, quantum efficiency, x-ray detection efficiency and detection efficiency are concepts which can be seen in connection with evaluations of image information transfer properties or noise properties of screen-film systems (Wagner and Weaver, 1975, 1976; Wagner, 1976; Dick and Motz, 1981). Since physical definitions of these concepts are usually not given by the authors they are not readily understood nor immediately applicable in other studies. It would seem, however, that the attenuation of photons by the screens yields a good quantification of these concepts. This is not in agreement with the concept "x-ray quantum-detection efficiency" of phosphor-screen-film combinations, as defined by Stevels and Pingault (1975) in a report on  $\text{BaFCl}$ -phosphor.

It appears that the attenuation of photons by intensifying screens can provide useful information in many application areas. Since it is easily

determined, it seems reasonable to employ this physical property as a first-order approximation of other physical properties, which are more difficult to quantify. Since the attenuation is often not the quantity of main interest, few reports on this physical property of intensifying screens are found in the literature. The attenuation of monoenergetic photons of intensifying screens of various chemical composition has been reported by Vyborny (1976). In these measurements, Vyborny used K x-rays which were emitted from metal targets (Doi et al., 1982).

An extensive investigation is made here of the attenuation of photons by intensifying screens of various composition, see Table 1. The attenuation of photons between 20 keV and 120 keV was measured by use of multi-channel analyzer and a broad bremsstrahlung distribution. The attenuation by the intensifying screens was hereby determined simultaneously at many different monoenergetic photon energies. The experimentally determined attenuations are compared with attenuations calculated from mass attenuation coefficients of the phosphor materials (Storm and Israel, 1967). The mean attenuations by the screens are also determined at twenty different bremsstrahlung distributions, simulating those occurring in various diagnostic x-ray examinations (Holje, 1983 f). These are obtained by weightings according to the distributions of photons.

The high attenuations in some of the screens investigated provide the basis for an analysis of the construction of asymmetric screen-pairs. In this context, single screen systems are suggested as an advantageous alternative to thick screen pair systems.

TABLE 1

| Manufacturer | Trade name        | Phosphor                                                                              | Dominating K-abs/keV |
|--------------|-------------------|---------------------------------------------------------------------------------------|----------------------|
| Agfa-Gevaert | M.R. 50           | LaOBr:Tb                                                                              | 38.93                |
|              | M.R. 200          | "                                                                                     | "                    |
|              | M.R. 400          | "                                                                                     | "                    |
|              | M.R. 600          | "                                                                                     | "                    |
| CAWO         | SE 2              | LaOBr:Tb                                                                              | 38.93                |
|              | SE 4              | "                                                                                     | "                    |
|              | SE 6              | "                                                                                     | "                    |
| DuPont       | Cronex Par Speed  | CaWO <sub>4</sub>                                                                     | 69.53                |
|              | Cronex Quanta II  | BaFCl:Eu                                                                              | 37.44                |
| Fuji         | Grenex G-4        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                |
|              | Grenex G-8        | "                                                                                     | "                    |
| General El.  | Blue Max 1        | LaOBr:Tb                                                                              | 38.93                |
|              | Blue Max 2        | "                                                                                     | "                    |
| Ilford       | Rare Earth        | LaOBr:Tm                                                                              | 38.93                |
| Kodak        | X-Omatic Regular  | BaSO <sub>4</sub> :Eu/SrSO <sub>4</sub> :Eu                                           | 37.44/16.11          |
|              | Lanex Fine        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                |
|              | Lanex Regular     | Gd <sub>2</sub> O <sub>2</sub> S:Tb/La <sub>2</sub> O <sub>2</sub> S:Tb <sup>1)</sup> | 50.24/38.93          |
| Philips      | Type 4360         | BaFCl:Eu                                                                              | 37.44                |
|              | Type 6359         | "                                                                                     | "                    |
| Siemens      | Rubin Super       | CaWO <sub>4</sub>                                                                     | 69.53                |
|              | Titan 923         | LaOBr:Tb                                                                              | 38.93                |
| 3M           | Trimax Alpha 4    | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                |
|              | Trimax Alpha 8    | "                                                                                     | "                    |
| U.S. Radium  | Rarex BG Detail   | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>2)</sup>  | 50.24/17.04          |
|              | Rarex BG Mid Sp.  | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>3)</sup>  | 50.24/17.04          |
|              | Rarex BG High Sp. | "                                                                                     | "                    |
|              | Rarex B Mid Sp.   | Y <sub>2</sub> O <sub>2</sub> S:Tb                                                    | 17.04                |

1) 93% / 7 % by weight 2) 60 %/40 % by weight 3) 75 %/25 % by weight

## 2. MEASUREMENTS AND CALCULATIONS.

### 2.1 The detector and radiation source.

The x-ray detector used in the measurements was a lithium-drifted germanium detector, with a response variation of  $\pm 1\%$  within an area of 11 mm in diameter. Measured pulse-height distributions were converted to true photon spectra by taking into account full energy peak efficiency, fluorescent energy loss and Compton scattering loss, which were obtained from the Monte Carlo simulation (Svahn, 1977). The determination of true photon distributions made it possible to simplify the attenuation measurements. Instead of using monoenergetic radiation sources, a bremsstrahlung distribution, which covers the wide energy range of interest, could be used. The attenuation by the intensifying screens was hereby determined simultaneously at many different monoenergetic photon energies. Since this study is concerned with screen-film responses to filtered x-ray beams between 60 and 120 kV, a photon distribution produced at 130 kV without extra filtration was used to yield the attenuation data needed. The photon fluence rate, reaching the detector was kept low in order to prevent dead-time losses from introducing any significant uncertainties to the attenuation determinations. The photon fluence rates used in the measurements introduced less than 5 % dead-time losses.

### 2.2 The geometry of the experimental set-up.

The geometry of the experimental set-up together with the diameters of the collimators are shown in Figure 1. The first collimator in front of the x-ray tube efficiently eliminates off-focus radiation, the second lead collimator is to collimate the beam, whereas the gold collimator serves as a pin-hole camera. By this arrangement, an image of the focal spot, with an area of approximately  $3.5 \text{ mm}^2$  ( $2.2 \times 1.6 \text{ mm}^2$ ) is projected on the intensifying screens. The size of this area is a compromise between the necessity of using a large field size, to even out possible inhomogeneities of the fluorescent layers, and the need to use small screen areas producing negligible amounts of secondary radiation, which might reach the detector. The collimator placed in front of the screens is



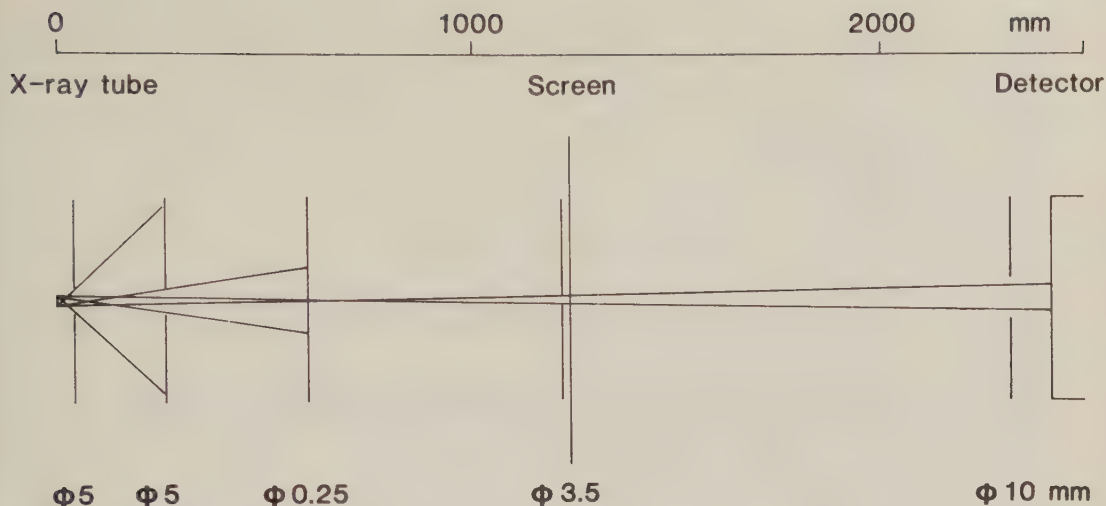


Figure 1. The geometry of the experimental set-up for attenuation measurements. The collimator with the aperture 0.25 mm is made of 5.8 mm Au. The other collimators are made of 20 mm Pb.

for further field definition and the collimator in front of the detector is to prevent secondary radiation from being incorporated in the measurements. This geometry allows a fraction of only  $5 \times 10^{-6}$  of the radiation, emitted isotropically from a point in the irradiated area of the intensifying screens, to reach the detector. The diameter of the field, irradiating the detector, is slightly less than 8 mm, which is well within the area where the detector response is homogeneous.

### 2.3 Attenuation measurements at photon energies between 20 keV and 120 keV.

The high tension applied over the x-ray tube was continuously controlled by use of a high tension divider. The radiation output was monitored by means of an ionization chamber, which was placed between the first and second lead collimators. The pulse height distributions, with and without the screen pairs in the radiation field, were measured with the multi-channel analyzer at a channel width of 40 eV. After corrections for the detector response, to give the true photon spectra, the attenuation,  $A$ , was calculated according to the formula;

$$A = \frac{\frac{d\phi_0}{dh\nu} - \frac{d\phi}{dh\nu}}{\frac{d\phi_0}{dh\nu}}$$

$\frac{d\phi_0}{dh\nu}$  is the differential photon fluence impinging upon the screens

$\frac{d\phi}{dh\nu}$  is the differential photon fluence transmitted through the intensifying screens

Data was then averaged in intervals of 25 channels to give attenuation data at each keV between 20 and 120 keV.

Since these evaluations involve quotients of corresponding portions of two different x-ray spectra (the incident and the transmitted), it is necessary to maintain a high reproducibility of the radiation distribution emitted from the x-ray tube. As described in a previous section, the high tension was controlled within  $\pm 1$  kV. The accuracy of this setting is very critical. Small changes in the high tension will especially affect the high energy part of the x-ray spectrum and the output of characteristic radiation from the tungsten anode. Comparatively high uncertainties are therefore to be expected in attenuation data for high energy photons, when evaluated by means of broad x-ray spectra. In addition, small variations in the high tension will also affect the fluence rate of the radiation emitted. Since the monitoring ionization chamber responds to the integrated distribution of x-rays, its signal cannot be used to properly correct for output variations caused by variations in the high tension. This limitation will result in uncertainties in the measured attenuation at all energies studied.

#### 2.4 Attenuation measurements at discrete photon energies.

In addition to the evaluations by means of the photon distribution covering the complete energy range of interest, the attenuation was deter-

mined at two discrete energies. The radioactive source, producing these monoenergetic photons, consisted of  $^{57}\text{Co}$  deposited on a tungsten support. 122 keV photons emitted by the cobalt isotope and tungsten  $K_{\beta 1}$  radiation, 67.2 keV, excited by the 122 keV photons, were used to irradiate a screen area of about  $8\text{ mm}^2$ . The transmittance was measured at two arbitrarily selected locations of all screen pairs and the mean values were determined.

The attenuation data thus achieved at 67.2 keV and 122 keV had statistical uncertainties less than  $\pm 1\%$  and  $\pm 0.3\%$  respectively. 82 % of the individual attenuation determinations at 67.2 keV deviated by less than  $\pm 2\%$  from their calculated mean values (68 % deviated by less than  $\pm 1\%$ ). These discrepancies between the attenuation measurements are probably mainly due to slight differences in the thicknesses of the screens at the two measuring locations. By means of these data, it was possible to reduce some of the uncertainties associated with the ionization chamber signal in the former measuring method. The accuracy of the absolute values of previous data could thus be improved by a normalization to data obtained at the discrete energy of 67.2 keV. (Data at this energy, determined by the broad photon distribution, were found to deviate by less than  $\pm 10\%$  from those determined by the monoenergetic radiation; data on two thirds of the screen pairs deviated by less than  $\pm 5\%$ ).

A shift in the spectral distribution of the broad x-ray beam used in the transmittance measurements (i.e. a shift in high tension) compared to that registered as "incident" x-ray distribution, however, resulted in a gradual distortion in attenuation data over the whole energy range. This distortion is, however, larger at high photon energies. The degree of such a distortion was evaluated by comparing the interrelation between the attenuations of 67.2 keV photons and 122 keV photons, determined with broad x-ray distribution and monoenergetic photons, respectively. After normalization of the attenuation, covering the broad energy range, to data obtained using monoenergetic 67.2 keV photons, some of the attenuation data at 122 keV were found to deviate by as much as 6 %, in absolute values, from those evaluated by the monoenergetic photons. - The low out-

put of photons in the high energy fraction of the x-ray distribution also contributes to these high fluctuations in the attenuation data -. For this reason, the attenuation data between 71 keV and 120 keV, were replaced by data achieved through an interpolation between the attenuation data determined at the two discrete energies, 67.2 keV and 122 keV. This was done for all screen pairs except for the calcium tungstate screens, where the K-absorption discontinuity of tungsten, 69.53 keV, falls between these two photon energies.

## 2.5 Attenuation determined from mass attenuation coefficients of the phosphors.

Data, published by Storm and Israel (1967), on mass attenuation coefficients of the elements composing the fluorescent layers, were used in determining the mass attenuation coefficients of the phosphors\* according to the following relation:

$$\mu/\rho = \sum_n (\mu/\rho)_n \cdot \omega_n \quad (1)$$

$(\mu/\rho)_n$  is the mass attenuation coefficient of the n<sup>th</sup> element

$\omega_n$  is the fraction by weight of the n<sup>th</sup> element

These mass attenuation coefficients, determined at photon energies between 10 keV and 150 keV of the various phosphors, are described elsewhere (Holje, 1983, e).

The thicknesses, d, of the screen pairs were determined from their transmittances, T, of monoenergetic 67.2 keV photons according to the equation:

$$d = (\mu/\rho)^{-1} \cdot \ln T \quad (2)$$

$\mu/\rho$  is the mass attenuation coefficient at 67,2 keV determined by Equation 1

\* Attenuation by binder and base have been neglected, since these are composed of low atomic elements.

By knowing the thickness and the mass attenuation coefficients, the attenuation,  $A$ , by the screen pairs of photons over the complete energy range of interest can now be determined from the relationship:

$$A = 1 - e^{-\mu/\rho \cdot d} \quad (3)$$

The agreement between the calculated and the experimentally determined attenuations is described in the next section.

## 2.6 Attenuation of x-ray distributions.

The aim of this study is to determine the physical properties of screen-film systems when used in clinical situations, and the main interest is therefore not focussed on their response to monoenergetic radiation, but on clinically relevant distributions. Information about the response to monoenergetic radiation is, however, important, because it can easily be applied to broad spectral distributions to obtain the response to any x-ray spectrum.

The radiation qualities used in this investigation are those produced at the x-ray tube potentials 60, 80, 100 and 120 kV filtered with 5, 10, 15, 20 and 25 mm aluminium. These radiation qualities and their spectral distributions are described in detail elsewhere (Holje, 1983 f). By weighting the experimentally determined attenuation of monoenergetic photons according to these spectral distributions, the attenuations at the radiation qualities of current interest are achieved according to the relation:

$$A_{x,y} = \frac{\int_{h\nu \text{ min}}^{h\nu \text{ max}} A_{h\nu} \cdot \left(\frac{d\Phi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu \text{ min}}^{h\nu \text{ max}} \left(\frac{d\Phi}{dh\nu}\right)_{x,y} dh\nu} \quad (4)$$

$A_{x,y}$  is the attenuation by the screens of the x-ray distribution produced at x kV filtered with y mm aluminium

$A_{h\nu}$  is the attenuation of photons with energy  $h\nu$

$\left(\frac{d\Phi}{dh\nu}\right)_{x,y}$  is the differential photon fluence produced at x kV filtered with y mm aluminium

$h\nu \text{ min}$  and  $h\nu \text{ max}$  are the minimum and maximum photon energies.



Due to the large number of screens incorporated in the study, the attenuation data will be presented in a concise, but still comprehensive, way. Absolute attenuation values will therefore be given at only one radiation quality, namely at that produced at 80 kV filtered with 20 mm aluminium. The influence of the radiation quality on the attenuation by all of the intensifying screens, with fluorescent layers of the same chemical composition, will be treated jointly and presented as normalized to the radiation quality of 80 kV and 20 mm aluminium. Information on absolute values for all screen pairs investigated can be derived at the various radiation qualities from data thus presented.

## 2.7 Determinations of the screen thicknesses.

The transmittance of monoenergetic 67.2 keV photons through all of the front screens,  $T_f$ , was measured in the same way as that through the screen-pairs,  $T_p$ , described in section 2.4. From these data, the transmittance through the back screens,  $T_b$ , which is equal to  $T_p/T_f$ , was determined. These transmittance data, together with appropriate mass attenuation coefficients of the phosphors, were used in the determinations (Equation 2), of the thicknesses of the screen pairs and the two screens composing the screen pairs. The thickness determinations of the back- and front screens were performed, since five of the screen pairs, namely Ilford Rare Earth, Du Pont Cronex Quanta II, Siemens Rubin Super, Fuji G-rex G-8 and Kodak Lanex Regular, had differing front- and back screens. These intensifying screens were manufactured with thicker back screens to compensate for the reduced amount of radiation existing behind the front screens, thus striving to achieve the same absorbed energy in the back screen as that in the front screen. All other screen pairs were symmetric, i.e. no distinction was made between front- and back screens, but records have been kept throughout this investigation so that the same screens have been consistently used as front- or back screens. The thicknesses of both screens were calculated.

## 2.8 Asymmetric screen pairs; a theoretical consideration using monoenergetic radiation.

Only five out of all the 27 screen pairs investigated are asymmetric.

From this it is apparent that most screen manufacturers do not consider that the sensitivity gain, which can be obtained with a thicker back screen, is large enough to be worth the extra cost and inconvenience of manufacturing different front- and back screens. If a screen pair absorbs only a small amount of radiation, 20 % or less, there is no need for asymmetric screens. The necessity of a thick back screen becomes more pronounced when the screen absorption is high.

The attenuation in a screen pair,  $A_p$ , can be expressed by means of the transmission through the front screen and the back screen:

$$A_p = 1 - T_p = 1 - T_f \cdot T_b \quad (5)$$

$T_p$ ,  $T_f$  and  $T_b$  are the transmissions through a screen pair, front screen and back screen, respectively

In a symmetric screen pair:

$$A_b = A_f \text{ or equivalently } T_b = T_f \quad (6)$$

$A_f$  and  $A_b$  are the attenuations in front screen and back screen

In an asymmetric screen pair, where the same number of photons are to be attenuated\* in the two screens, the equation becomes:

$$\Phi_0 \cdot A_f = \Phi_f \cdot A_b \text{ or} \quad (7)$$

$$A_b = A_f / (1 - A_f) \text{ or equivalently}$$

$$T_b = (2T_f - 1) / T_f$$

$\Phi_0$  is the radiation fluence incident on the screen pair, and  $\Phi_f$  is the fluence transmitted through the front screen and thus incident on the back screen. (Attenuation in the film is neglected).

\* In this way equal energy is presumed to be absorbed in the two screens to yield the same light production. Light absorption is neglected and therefore the same amount of light will be emitted from the front- and back screens.

From Equation 2, the thicknesses of the front screen and the back screen and their ratio become:

$$d_f = (\mu/\rho)^{-1} \cdot \ln T_f$$

$$d_b = (\mu/\rho)^{-1} \cdot \ln T_b \quad \text{so that}$$

$$d_b/d_f = \ln T_b / \ln T_f \quad (8)$$

By means of the above equations, the attenuation in front- and back screens of asymmetric screen pairs, and also the increase in thickness of the back screens, can be calculated. Table 2 shows the data achieved at various levels of attenuation in the screen pair and on the condition that the same number of photons are attenuated in front- and back screens.

Table 2

| $A_p$ | $A_f$ | $A_b$ | $d_b/d_f$ |
|-------|-------|-------|-----------|
| 0.2   | 0.10  | 0.11  | 1.1       |
| 0.3   | 0.15  | 0.18  | 1.2       |
| 0.5   | 0.25  | 0.33  | 1.4       |
| 0.7   | 0.35  | 0.54  | 1.8       |

Table 2 shows that the thickness ratio between back- and front screens should be only 1.1 when 20% of the radiation is attenuated in the screen pair. Thus, as was previously stated, one can conclude that there is no need for asymmetric screens when the attenuation is 20 % or less. At high attenuations of 30 %, 50 % and 70 %, the thickness ratio between back- and front screens become 1.2, 1.4 and 1.8 respectively, if the reduced amount of radiation behind the front screens is to be compensated for. The need for asymmetric screen pairs here is obvious.

### 3. RESULTS AND DISCUSSION.

#### 3.1 The attenuation at photon energies between 10 keV and 120 keV.

The results of the attenuation determinations at photon energies between 10 and 120 keV are shown in Figures 2 and 3. The twenty-seven intensifying screens investigated have been divided into groups according to the chemical composition of their fluorescent layers, one screen from each group is presented. The lines indicate the attenuation as determined from mass attenuation coefficients. The experimental determinations, which were made in steps of 1 keV, are indicated here by the data points at every tenth keV. A normalization between the calculated and measured attenuation data is automatically achieved at 67.2 keV. The reason for this is that the screen thicknesses, used in the calculations, were determined from measured attenuation at 67.2 keV. The attenuations determined here agree within 2 % with those determined by Vyborny (1976) on comparable screens.

Figures 2 and 3 clearly illustrate the good agreement between measured and calculated attenuation. Since similar good agreements were found for all of the intensifying screens investigated, one can conclude that it is quite possible to make use of broad x-ray distributions when evaluating attenuation over a wide energy range. Small, unavoidable, variations in the x-ray tube potential, combined with the low relative output of high energy photons in the x-ray distributions, however, result in large uncertainties in attenuation data determined by use of the high energy fraction of the spectral distribution. For this reason, therefore, the high tension used to produce the x-ray distribution should be well above the highest energy at which the attenuation is to be determined. The important finding is that, with correct information about the composition of the fluorescent layers and with the correct attenuation at one photon energy, the attenuation at any energy can be calculated by use of mass attenuation coefficients. Experimental evaluations, however, have the great advantage that they give "true" data. Two examples of this were

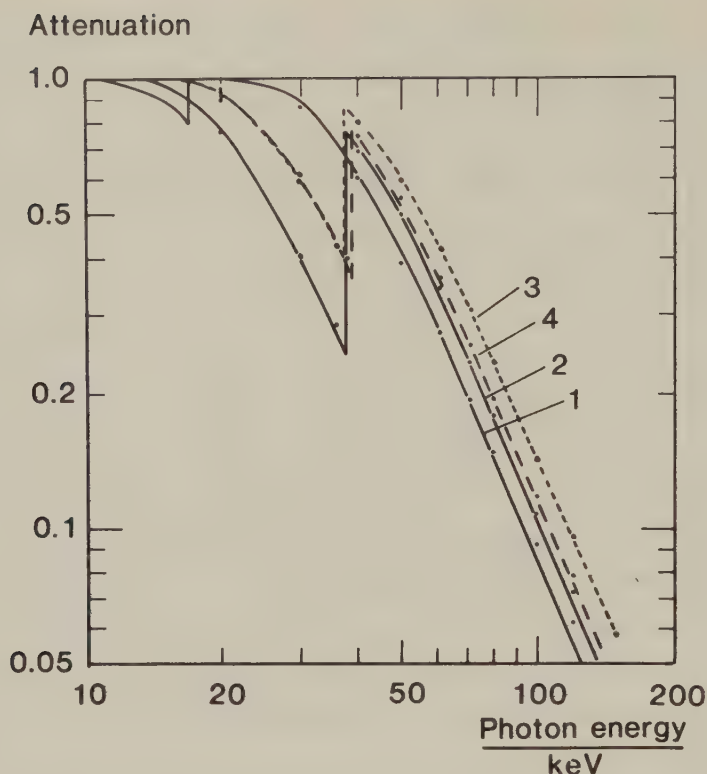


Figure 2. The attenuation of monoenergetic photons in (1) Rarex B Mid Speed screens,  $\text{Y}_2\text{O}_2\text{S}$ , (2) Philips Type 4360 screens,  $\text{BaFCl}$ , (3) X-Omatic Regular screens,  $\text{BaSO}_4$  and (4) M.R. 200 screens,  $\text{LaOBr}$ .

found among the screens in this study: The Lanex Regular screens were composed of a mixture of  $\text{La}_2\text{O}_2\text{S}$  and  $\text{Gd}_2\text{O}_2\text{S}$ , according to the manufacturer. The exact percentage of the mixture was not given, since these were, obviously, experimental screens made at an early stage (1976). (Screens manufactured in 1979 are made of pure gadolinium oxysulphide.) A small K-absorption edge of lanthanum was found by means of the attenuation measurements. Calculations, using the mass attenuation coefficients at the K-absorption energies of lanthanum and gadolinium, showed that these screens were composed of 6 % lanthanum oxysulphide and of 94 % gadolinium oxysulphide. This minute content of lanthanum oxysulphide is hereafter disregarded, and the screens are treated as pure gadolinium oxysulphide screens. Another finding was that the K-absorption edge of europium was



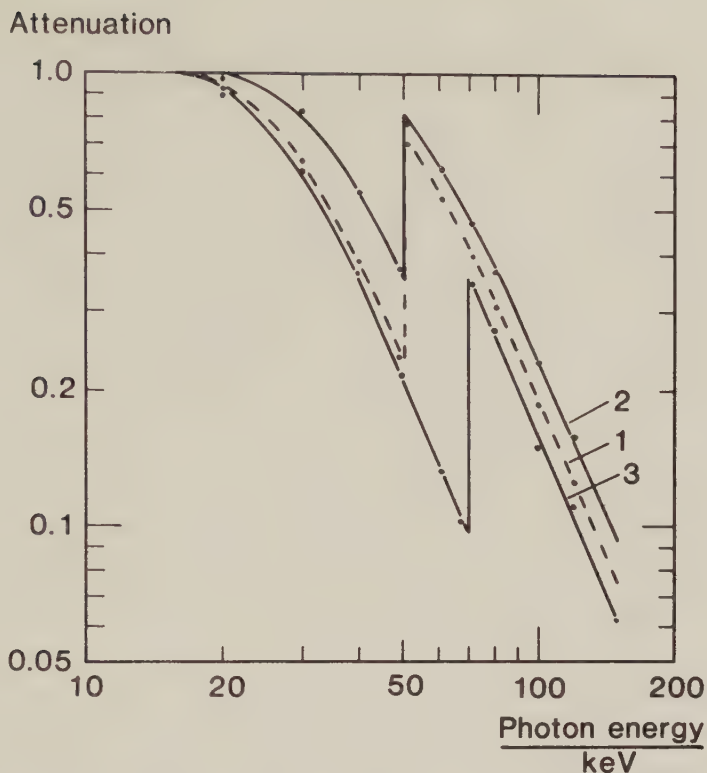


Figure 3. The attenuation of monoenergetic photons in (1) Grenex G-4 screens,  $\text{Gd}_2\text{O}_2\text{S}$ , (2) Rarex BG Mid Speed screens,  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ , (3) Cronex Par Speed screens,  $\text{CaWO}_4$ .

clearly distinguished in one of the screens made of barium fluorochloride. This is quite remarkable, since europium is used here as an activator and only a tiny amount of this element is usually added.

Yttrium screens. In Figure 2, the calculated attenuation of the yttrium oxysulphide screens shows the K-absorption edge of yttrium to be at 17.04 keV. No experimental determinations were made below 20 keV, since none of the x-ray distributions employed in this study contain photons of such low energies.

Barium screens. The K-absorption edge of barium at 37.44 keV is illustrated by both calculated and measured photon attenuations for a pair of barium fluorochloride screens, and also for a pair of barium sulphate/strontium sulphate screens. Figure 2 shows that there is a distinct dif-

ference in relative photon attenuation between these two screen pairs, depending on whether the incident photon energy is lower or higher than that of the K-edge of barium. This is due to the fact that the barium content is different in these two phosphor materials. BaFCl consists by 72 % barium, whereas this specific mixture of  $\text{BaSO}_4$  and  $\text{SrSO}_4$  contains only 47 % barium. This makes the elements, other than barium, more influential on the attenuation properties in  $\text{BaSO}_4/\text{SrSO}_4$ -screens than in BaFCl-screens. Since barium dominates the attenuation characteristics when the incident photon energies are higher than that of the K-absorption edge, one can expect the low atomic components to have significant influence only when the photon energies are lower than 37.44 keV. The increased attenuation in the  $\text{BaSO}_4/\text{SrSO}_4$ -screens, relative to that in the BaFCl-screens, below this energy is thus due to their higher relative content of low atomic components.

Lanthanum screens. Since lanthanum and barium are neighbours in the periodic system, the attenuation characteristics of screens with either of these elements as high atomic elements can be expected to be rather similar. Figure 2 shows the close similarities that exist between the M.R. 200 screens made of LaOBr and the X-Omatic Regular screens made of  $\text{BaSO}_4/\text{SrSO}_4$  over the complete range. Not only are their K-absorption edges close as to energy,  $E_K$  (lanthanum) = 38.93 keV, but their discontinuous jumps are almost identical. The attenuation characteristics of the BaFCl-screens, however, differ from those of these two screen pairs. This again illustrates that the low atomic components may be rather influential on the attenuation of photons with energies lower than that of the K-absorption edge of the high atomic number element.

Gadolinium screens. The photon attenuation by the Grenex G-4 screens made of  $\text{Gd}_2\text{O}_2\text{S}$  is illustrated in Figure 3. These screens have their K-absorption discontinuity at 50.24 keV. An interesting comparison of the screens made of gadolinium oxysulphide and calcium tungstate can be made by means of the results shown in Figure 3. At photon energies lower than that of the K-absorption edge of gadolinium and also higher than that of tungsten, the photon attenuation in this screen pair of gadolinium oxy-

sulphide is only somewhat higher than that in the calcium tungstate screens, but between these two discontinuities, it is more than four times higher. When these two screen pairs, therefore, are exposed to x-ray distributions with maximum photon emittance at energies between 50 keV and 70 keV, the gadolinium oxysulphide screens will attenuate the largest number of photons. With the radiation qualities incorporated in this study, the screen pair of  $\text{Gd}_2\text{O}_2\text{S}$  attenuates between 1.2 and 2.4 times more photons than the screen pair of  $\text{CaWO}_4$ . The maximal difference was found at 80 kV filtered with 25 mm aluminium.

Gadolinium/Yttrium screens. The photon attenuation by screens made of a mixture of yttrium oxysulphide and gadolinium oxysulphide is represented by the Rarex BG Mid Speed screens in Figure 3. Their attenuation, relative to that of the pure gadolinium oxysulphide screens, increases at photon energies lower than the K-absorption energy of gadolinium. This increase is due to photon attenuation in the yttrium oxysulphide phosphor.

Tungstate screens. The photon attenuation by the calcium tungstate Cronex Par Speed screens is shown in Figure 3. The K-absorption edge of tungsten at 69.53 keV is clearly illustrated. The K-absorption energy of yttrium oxysulphide screens is the lowest among the screens studied while that of the calcium tungstate screens is the highest. It will be seen in the following, that screens made of these two phosphors exhibit similar attenuation characteristics when exposed to many of the photon distributions encountered in this investigation.

### 3.2 The photon attenuation at 80 kV and 20 mm aluminium filter.

Table 3 presents the attenuation by all of the screen pairs at the radiation quality produced at 80 kV filtered with 20 mm aluminium. These data were derived by weighting the experimentally determined attenuation according to the x-ray spectral distribution described elsewhere (Holje, 1983 f). The screens are listed according to the chemical composition of their fluorescent layers. Previous investigations (Holje et al., 1977; Holje and Doi, 1982) have concluded that the M.R. screens, Blue Max screens and SE screens were essentially the same screens marketed under different names. This conclusion was based on the fact that the attenuation, sensitivity and resolution properties of the M.R. 200, Blue Max 1 and SE 2 screens were the same. Similar results were obtained for M.R. 400, Blue Max 2 and SE 4, as well as for M.R. 600 and SE 6 screens. For this

TABLE 3

| Intens.<br>screen | Att.80kV,<br>20 mm Al | Thickn.<br>mg/cm <sup>2</sup> | Intens.<br>screen | Att.80kV,<br>20 mmAl | Thickn.<br>mg/cm <sup>2</sup> |
|-------------------|-----------------------|-------------------------------|-------------------|----------------------|-------------------------------|
| M.R. 50 front     |                       | 30                            | Cronex front      |                      | 32                            |
| back              |                       | 31                            | Par Speed back    |                      | 29                            |
| pair 0.37         |                       | 61                            | pair 0.21         |                      | 61                            |
| M.R.200 front     |                       | 37                            | Rubin front       |                      | 34                            |
| back              |                       | 38                            | Super back        |                      | 44                            |
| pair 0.43         |                       | 75                            | pair 0.25         |                      | 78                            |
| M.R.400 front     |                       | 33                            | Grenex front      |                      | 39                            |
| back              |                       | 35                            | G-4 back          |                      | 43                            |
| pair 0.40         |                       | 68                            | pair 0.47         |                      | 82                            |
| M.R.600 front     |                       | 61                            | Grenex front      |                      | 45                            |
| back              |                       | 60                            | G-8 back          |                      | 68                            |
| pair 0.57         |                       | 121                           | pair 0.57         |                      | 113                           |
| SE 2              | see M.R. 200          |                               | Lanex front       |                      | 32                            |
| SE 4              | see M.R. 400          |                               | Fine back         |                      | 38                            |
| SE 6              | see M.R. 600          |                               | pair 0.42         |                      | 70                            |
| Blue Max 1        | see M.R. 200          |                               | Lanex front       |                      | 65                            |
| Blue Max 2        | see M.R. 400          |                               | Regular back      |                      | 76                            |
| Rare front        |                       | 36                            | pair 0.64         |                      | 141                           |
| Earth back        |                       | 67                            | Trimax front      |                      | 31                            |
| pair 0.51         |                       | 103                           | Alpha 4 back      |                      | 30                            |
| Titan front       |                       | 34                            | pair 0.38         |                      | 61                            |
| 923 back          |                       | 38                            | Trimax front      |                      | 55                            |
| pair 0.41         |                       | 72                            | Alpha 8 back      |                      | 56                            |
| Cronex front      |                       | 34                            | pair 0.57         |                      | 111                           |
| Quanta back       |                       | 50                            | Rarex BG front    |                      | 44                            |
| II pair 0.47      |                       | 84                            | Detail back       |                      | 37                            |
| Type front        |                       | 32                            | pair 0.40         |                      | 81                            |
| 4360 back         |                       | 35                            | Rarex BG front    |                      | 61                            |
| pair 0.40         |                       | 67                            | Mid Sp. back      |                      | 65                            |
| Type front        |                       | 48                            | pair 0.57         |                      | 126                           |
| 6359 back         |                       | 49                            | Rarex BG front    |                      | 83                            |
| pair 0.50         |                       | 97                            | High Sp. back     |                      | 84                            |
| X-Omat. front     |                       | 68                            | pair 0.67         |                      | 167                           |
| Regular back      |                       | 62                            | Rarex B front     |                      | 65                            |
| pair 0.49         |                       | 130                           | Mid Sp. back      |                      | 59                            |
|                   |                       |                               | pair 0.34         |                      | 124                           |

reason, and since these screens will be modified in the near future, attenuation measurements in this study were only done on the M.R. screens. For practical purposes, the M.R. 200 data are expected to be applicable for the Blue Max 1 and SE 2 screens, the M.R. 400 data to be valid for the Blue Max 2 and SE 4 screens, and the M.R. 600 data to be valid for the SE 6 screens, as indicated in Table 3.

Data in Table 3 show that the new screens incorporated in the study attenuate between 35 and 65 per cent of the incident photon fluence. The two calcium tungstate screens studied here attenuate only 20-25 % of the photon fluence. In an earlier investigation (Holje and Svahn, 1974) where 14 different calcium tungstate screens were studied, the attenuation at the radiation quality produced with 80 kV and 20 mm aluminium showed values between 15 and 50 per cent. These maximal values are fairly similar to the data for the new screens. From this comparison, it is evident that the sensitivity gain of 2-4 times, achieved with the new screen-film systems, is not only due to higher attenuation, but must partly be accomplished by the higher light-yield of the new screens.

In Figure 4 the attenuation by the screen pairs of the photon fluence produced at 80 kV filtered with 20 mm aluminium is plotted versus the calculated screen pair thicknesses (Table 3). This presentation gives a clear picture of the favourable attenuation characteristics existing in most of the new phosphor screens. At this radiation quality, the attenuation by these screens may exceed that of calcium tungstate screens of equivalent thicknesses by as much as a factor of 1.8.

The photon distribution produced at 80 kV filtered with 20 mm aluminium can be approximated to a triangular distribution, ranging from 30 keV to 80 keV with peak emission half-way between, i.e. at 55 keV (Holje, 1983 f). The high attenuation of this photon distribution by screens with a high Z-element of lanthanum, barium or gadolinium is an immediate consequence of the favourable location of their K-absorption discontinuities. These are located between 37 and 50 keV and these screens therefore have their maximum attenuation in the energy interval where the incident photon fluence is the highest (see Figures 2 and 3).



# Attenuation

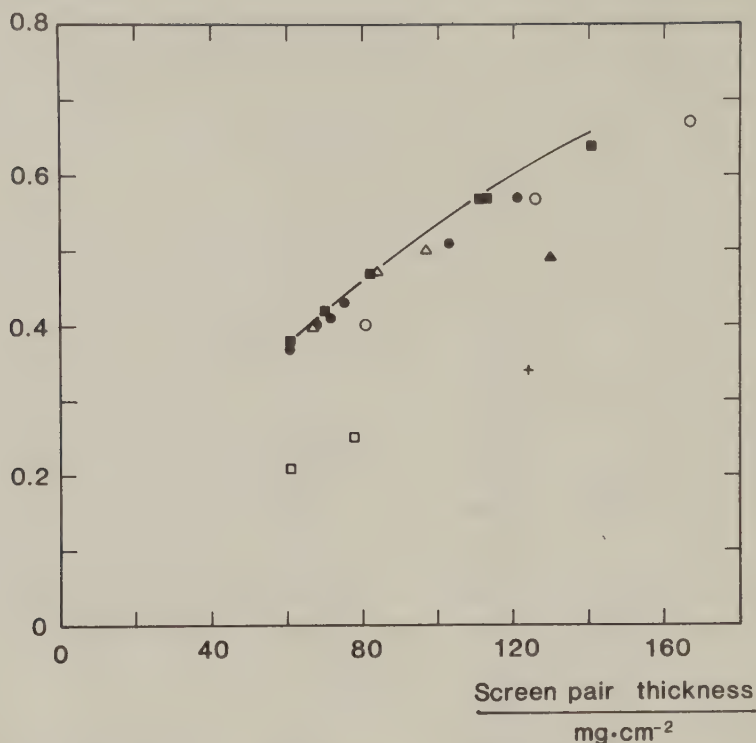


Figure 4. The attenuations by the screen pairs at 80 kV filtered with 20 mm aluminium versus their thicknesses.  
 +—Y<sub>2</sub>O<sub>2</sub>S-screens,  $\Delta$  BaFCl-screens,  $\blacktriangle$ —BaSO<sub>4</sub>/SrSO<sub>4</sub>-screens  
 ●—LaOBr-screens,  $\blacksquare$ —Gd<sub>2</sub>O<sub>2</sub>S-screens,  $\circ$ —Gd<sub>2</sub>O<sub>2</sub>S/Y<sub>2</sub>O<sub>2</sub>S-screens,  $\square$ —CaWO<sub>4</sub>-screens. The curve is fitted by eye to the experimental values on Gd<sub>2</sub>O<sub>2</sub>S-screens.

In calcium tungstate screens, the increase in attenuation, due to the commencement of K-shell interactions, occurs at about 70 keV, which is at the very high fraction of the energy interval covered by the incident photon distribution. Figure 3 shows that these screens have their lowest attenuation at energies where the incident photon fluence is highest. The low attenuation by these screens, shown in Figure 4, is a consequence of the poor adaptation between their attenuation characteristics and the incident spectral distribution of photons.

According to Figure 4, the attenuation in the yttrium oxysulphide screens is comparable to that in screens made of calcium tungstate. The K-shell discontinuity in these screens at approximately 17 keV is below the lowest energy of the incident photon distribution. The continuously decreasing

attenuations by these screens, shown in Figure 2, have great similarities to that of the calcium tungstate screens in the energy interval of interest; 30 to 80 keV. The resultant effect is the same, i.e. low attenuation of the incident photon distribution.

The results shown in Figure 4 establish that the radiation quality, produced at 80 kV filtered with 20 mm aluminium, is poorly attenuated by screens whose characteristics are dominated by a low Z-element like yttrium ( $Z=39$ ) or by a high Z-element like tungsten ( $Z=74$ ).

Maximal attenuation is obtained in screens dominated by elements having atomic numbers somewhere between these two extremes. This is verified by the high attenuation found in screens whose characteristics are dominated by lanthanum ( $Z=56$ ), barium ( $Z=57$ ) and gadolinium ( $Z=64$ ). Since this radiation quality simulates that existing behind 25 cm of human tissue (Holje, 1983 f), when exposed at the x-ray tube potential 80 kV, one can conclude that the latter screens are the better attenuators, when used in different clinical examinations.

### 3.3 The attenuation of x-ray distributions.

Figure 5 illustrates the relative attenuation by the screens at the various radiation qualities described elsewhere (Holje, 1983 f). Data are normalized to the attenuation 80 kV and 20 mm aluminium filter, and are presented as a function of aluminium filter thickness for each of the accelerating potentials: 60, 80, 100 and 120 kV.

Analysis of basic attenuation data, normalized in this way, indicates that differences in thickness and in low atomic number components of the screens have a minor influence, and that their attenuation properties are dominated by the elements with the highest atomic numbers. A result of these findings is that all intensifying screens, based on phosphor containing the same high atomic number elements, can be treated as a single group.

The calculated mean values of the attenuation by all of the screens belonging to the specific groups are indicated by the curves in Figure 5. To illustrate the magnitude of the variations within the different groups of screens, the highest and lowest attenuations registered at each radiation quality are plotted as bars in Figure 5. Barium sulphate/strontium sulphate screens and barium fluorochloride screens are all treated to-

gether in the barium group. The lanthanum, tungsten and gadolinium groups include all screens made of lanthanum oxybromide, calcium tungstate and gadolinium oxysulphide, respectively. The only yttrium oxysulphide screens incorporated in the study are indicated as an yttrium group and the screens composed of a mixture of gadolinium oxysulphide and yttrium oxysulphide are included in the gadolinium yttrium group.

An example of the influence of the screen thickness on the attenuation characteristics is shown by data for the screens belonging to the lanthanum group. The thicknesses of these screens differ by a factor of two, see Table 3. Data in Figure 3 indicate that this difference in screen thickness results in a discrepancy of less than 10 % in their attenuation dependence on radiation quality.

The influence of differences in low atomic number components on the attenuation characteristics cannot be unambiguously illustrated by the material used in this study. Although the barium group includes screens made of both  $\text{BaFCl}$  and  $\text{BaSO}_4/\text{SrSO}_4$ , one can not establish any clear effect caused by the phosphor composition. This is in part due to the fact that these screens differ in thickness. It is also due to the fact that the x-ray distributions used here have only small fractions of photons at energies where the influence of the low atomic number components of the phosphors may have any significant influence on the attenuation, i.e. below the K-absorption edge of barium at 37.44 keV (Sect. 3.1, Figure 2).

Yttrium screens. The yttrium oxysulphide screens have their principal K-absorption edge at 17.04 keV, which is lower than any photon energy in the x-ray distributions used in this study. In the energy range of interest, namely from 20 keV to 120 keV, the photon attenuation by yttrium oxysulphide screens, therefore, decreases continuously with increasing photon energy. This was illustrated with the attenuation by the Rarex B-Mid Speed screens in Figure 2. The consequence of this characteristic is that this screen pair, with only one exception, exhibits the greatest variation in the attenuation with changes in radiation quality. The only exception is found with the calcium tungstate screens when they are exposed to distributions of low energy photons. This is illustrated in Figure 5.

Relative attenuation

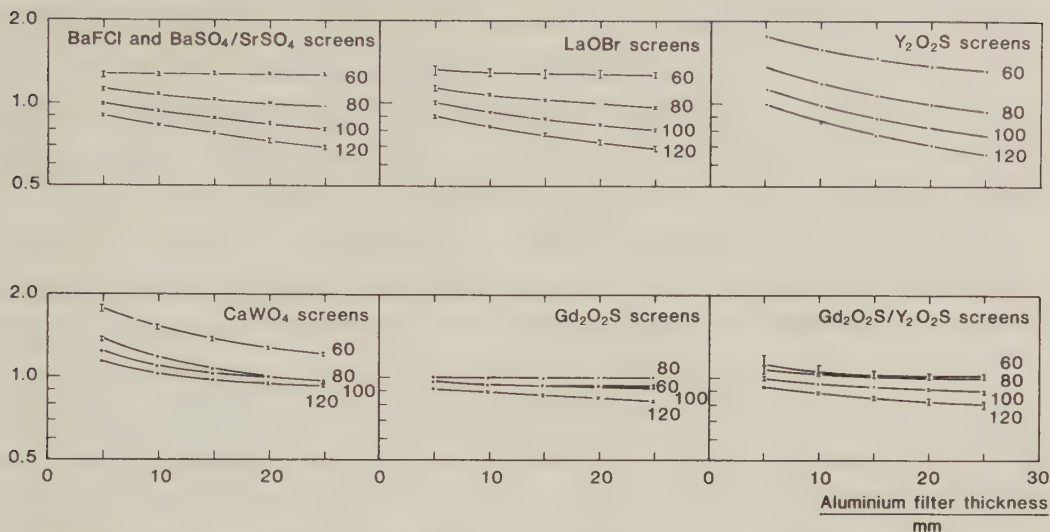


Figure 5. Attenuation by intensifying screens of different chemical composition at various incident radiation distributions relative to that at 80 kV filtered with 20 mm aluminium. Different x-ray tube potentials and aluminium filter thicknesses are used to produce these radiation distributions.

Barium and Lanthanum screens. Figure 5 shows that no distinction can be made between the attenuation properties of barium screens and lanthanum screens. This is due to the fact that these two elements are neighbours in the periodic system. The attenuation characteristics of these two groups of screens exhibit moderate variations with radiation quality:  $\pm 30\%$  around the normalization point at 80 kV and 20 mm aluminium filter. Variations in attenuation among screens within either of the two groups are small ( $\pm 5\%$  or less). The largest variations occur at 60 kV, and from this it can be concluded that influences of screen thickness and low atomic number components are more pronounced when low energy radiation is employed.

Gadolinium screens. Intensifying screens made of gadolinium oxysulphide have a remarkable flat response to variations in radiation quality. Less than 20 % variations are observed between the attenuation at any of the radiation qualities studied. Data on relative attenuation at 60 kV and 100 kV are equal, and they are slightly lower than the response to 80 kV. Data on the attenuation at 120 kV are slightly lower than those at 60 kV



and 100 kV.

In the monoenergetic case, the attenuation decreases with increasing photon energy until an absorption edge is reached, where the attenuation increases abruptly and then gradually decreases again. When radiation distributions are employed it is evident that the attenuation characteristics must be smoothed out to a certain degree, but that some of the basic behaviour may still remain. The attenuation data achieved with the gadolinium oxysulphide screens are a good illustration of this. These screens have their K-absorption discontinuity at 50.24 keV and not until 90 keV has the attenuation decreased to the value it had just before the K-edge, see Figure 3. With the x-ray distributions used here, an increase in attenuation, due to the contribution of K-shell interactions, is illustrated in Figure 5, where the attenuation at 80 kV is higher than that at 60 kV. The attenuation gradually decreases at 100 kV and 120 kV, but not to such a high degree as was observed in the screens already discussed. This is again attributed to the increased attenuation by gadolinium screens of photons with energies higher than 50.24 keV.

These screens also exhibit remarkably small variations in attenuation with changes in object thickness. Their attenuation at 80 kV, for example, is totally independent of variations in the thickness of the aluminium filters. Since sensitivity characteristics of screen-film systems are largely determined by attenuation properties, the sensitivity of gadolinium oxysulphide systems is expected to be almost independent of radiation quality. This constancy in response to various radiation distributions makes these systems appear as almost ideal detector systems in regard to their sensitivity. The resulting image contrast may, however, not turn out to be better compared to systems with a pronounced energy dependence. This is further dealt with in publications concerning energy absorption and sensitivity of screen-film systems (Holje, 1983 b; Holje, 1983 c).

Gadolinium/Yttrium screens. The attenuation by screens composed of a mixture of gadolinium oxysulphide and yttrium oxysulphide has slightly higher variations with radiation quality than that of the pure gadolinium oxysulphide screens. This is due to the influence on the attenuation by the



yttrium oxysulphide components of these screens. Measured responses of these mixed phosphor screens agree well with estimations made by means of the attenuation in screens made of pure phosphor materials.

Somewhat larger variations in attenuation are found among screens made of  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$  compared to those among screens made of other phosphors. This may not be a consequence of their thickness differences, but merely depend on the different contents of the two phosphors in these screens. This is also indicated by results obtained from the numerical estimations, using the two different phosphor contents.

Tungstate screens. Large variations in photon attenuation by calcium tungstate screens are found when they are exposed to radiation produced at 60 kV to 80 kV filtered with 5 to 25 mm aluminium. This result is due to the fact that all, or at least a considerable fraction of the photons in these distributions have energies between the L- and K-absorption edges of tungsten, which are 12.10 keV and 69.53 keV, respectively. Therefore, in this energy range, the photon attenuation by calcium tungstate screens decreases continuously with increasing photon energy. This is similar to that of the yttrium oxysulphide screens discussed above.

Figure 5 also shows that except for the 60 kV- and 80 kV spectra just described, the radiation quality has fairly small influence on the photon attenuation by screens in the tungsten group. Due to its abrupt discontinuity, one may intuitively regard the occurrence of a K-absorption edge as a disturbing momentum. This will be true when mono-energetic radiation is employed, but its effect is rather moderate when x-ray distributions are used. The attenuation in calcium tungstate screens gives an illustration of the smoothing or averaging of the detector response occurring when incident x-ray distributions experience a K-absorption edge of the detector material.

### 3.4 Screen thicknesses.

Table 3 presents the thicknesses of all of the front screens, back screens and screen pairs. These were calculated according to Equation 2, using data on their transmittance of 67.2 keV photons. These thickness determinations are subject to uncertainties due to the uncertainties connected

to the transmission measurements. (86 % of the two individual thickness determinations deviated by less than  $\pm 3$  % from their calculated mean values. 77 % deviated by less than  $\pm 2$  %, and 61 % of the thickness determinations deviated by less than  $\pm 1$  % from their mean values).

The first group of intensifying screens presented in this table are made of lanthanum oxybromide phosphors. It should be noted that the M.R. 400 screen pair is thinner than the M.R. 200, although the former has twice the sensitivity of the latter, when combined with the same film (none of these screens contains a dye). The thinnest and thickest screen pairs made of lanthanum oxybromide phosphors are the M.R. 50 and M.R. 600 screens. The M.R. 600 screens are twice as thick as the M.R. 50 screens. One screen pair in this group, namely Rare Earth, is manufactured with a thicker back screen than front screen. Data in Table 3 indicate that its back screen is almost twice as thick as its front screen. Quanta II, made of barium fluorochloride phosphor, is another screen pair with a thick back screen and a thin front screen. The back screen is about 1.5 times thicker than the front screen.

The low sensitive calcium tungstate screens, Rubin Super, are thicker than the Par Speed screen pair, but they contain dye, which reduces light diffusion in the phosphor layers to give improved resolution. The Rubin Super is the third asymmetric screen pair. The thickness of its back screen is about 1.3 times that of the front screen.

The next large group in Table 3 consists of screens made of gadolinium oxysulphide phosphors. Among these screens, the Lanex Fine and Lanex Regular screens represent the two extremes of thickness. The Lanex Regular screen pair is twice as thick as the Lanex Fine screen pair. Two screen pairs in this group are asymmetric, namely Grenex G-8 and Lanex Regular. The back screen of Grenex G-8 is about 1.5 times thicker than its front screen, whereas that of Lanex Regular is only 1.2 times thicker than its front screen.

Three screen pairs in Table 3, Rarex.BG Detail, Mid and High Speed, are made of a mixture of gadolinium oxysulphide and yttrium oxysulphide. The BG High Speed screens are twice as thick as the BG Detail screens.

This is the third case where two screen pairs with the same phosphor composition differ by a factor of two in thickness. The resulting sensitivity difference is discussed in detail in another publication (Holje, 1983 c). It can already be mentioned here that the sensitivity gains obtained by using the thicker screen pairs are between 3.3 and 8.5 times.

The last screen pair in Table 3, Rarex B Mid Speed, is made of yttrium oxysulphide phosphor. This screen pair is symmetric, according to the manufacturer, although data indicate that the screen used as the front screen is thicker than that used as the back screen. These unusual data on the thicknesses are probably due to uncertainties involved in the thickness determinations.

### 3.5 Asymmetric screen pairs.

The effect of x-ray distributions. The calculations, performed in section 2.8 of thickness ratios between the back screen and the front screen of a screen pair, were based on attenuation of monoenergetic photons. Since the attenuation of monoenergetic photons by the screens varies strongly over the energy range of interest, it is obvious that a single combination of asymmetric screens can not cover more than a small energy-range. The attenuation in the screen pairs investigated decreases from about 75-95 % at 20 keV down to 5-20 % at 120 keV. In practical clinical work, however, these variations are smaller, since broad x-ray distributions are used. With those radiation qualities employed in this investigation, the attenuation in the thinnest screen pair varies between 40-20 % and in the thickest screen pair the attenuation falls within 70-40 %. Another effect, which is introduced when x-ray spectra are used, is that the screens transmit the radiation selectively. The photon distributions reaching the back screens will thus not be attenuated to the same extent as those impinging upon the front screens. For this reason, the thickness ratio between the back screen and the front screen should be larger than estimated in the monoenergetic case.

Measured data. In Figure 6, the thickness ratios between back screens and front screens of the five asymmetric screen pairs are plotted versus their attenuations. The attenuations by the screen pairs of the twenty photon

## Thickness ratio

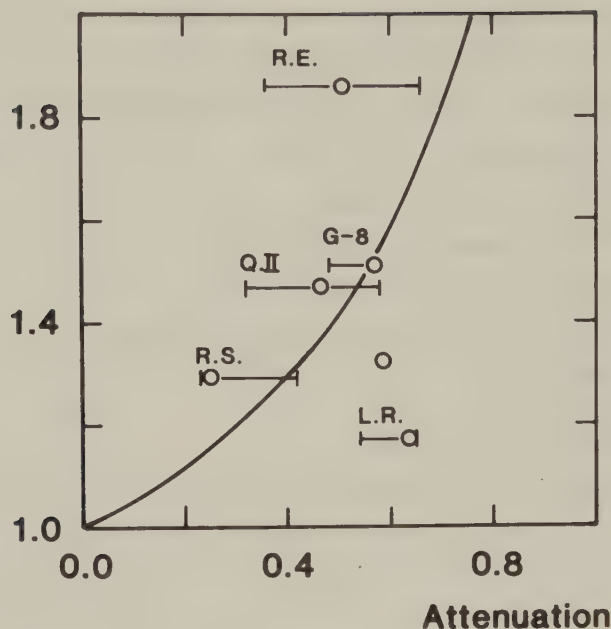


Figure 6. Thickness ratio between back screen and front screen versus the screen pair attenuation at various radiation qualities (R.E.) Rare Earth screens, (G-8) Grenex G-8 screens, (QII) Cronex Quanta II screens, (R.S.) Rubin Super screens, (L.R.) Lanex Regular screens. The curve shows the calculated thickness ratio for equal attenuation in back screen and front screen versus the screen pair attenuation of monoenergetic photons.

distributions employed (Holje, 1983 f) extend over attenuation intervals which are indicated by bars in the figure. Attenuation data at the radiation quality produced at 80 kV filtered with 20 mm aluminium are encircled. The curve in Figure 6 is calculated using monoenergetic radiation, see section 2.8.

To fulfil the requirements according to the discussion in the previous section on thickness ratios, when screens are exposed to broad photon distributions, measured data in Figure 6 should fall on, or to the left of, the theoretical curve. Only one of the screen pairs, the Lanex Regular, has a back screen which is much thinner than would be recommended from the predictions using monoenergetic radiation. In this case, the expected effect of asymmetry may not be fully achieved, and in this connec-



tion it is interesting to know that these screens, as manufactured today, are symmetric. Three of the screen pairs, the Quanta II, Rubin Super and Grenex G-8, have thickness ratios between their back screens and front screens which agree very well with those achieved through theoretical estimations. Data on the remaining screen pair, Rare Earth, indicate that the back screen is somewhat thicker than can be predicted theoretically.

Due to the uncertainties involved in the thickness determinations, data in Figure 6 must be treated with caution. In the case of the Rare Earth screens, therefore, one can conclude that the back screen is particularly thick. It is, however, hard to draw any conclusions about the exact magnitude of the thickness exaggeration.

The effect of light absorption. So far, no concern has been paid to how the absorbed energy is spatially distributed in the screens. This can, however, be an important factor. In previous calculations, asymmetric screen pairs were constructed so that the two screens were to attenuate the same number of photons. In this way, equal energy was presumed to be absorbed in the two screens and to yield the same light production. In the calculations, it was also assumed that no light absorption takes place in the screen material. Some of the light will, however, undergo absorption before reaching the film. This is especially true in screens containing a light absorbing dye, like the Rubin Super screens.

In view of the distribution of absorbed energy, it is easily realized that the greatest amount of light must be produced in the entrance layer of the front screen and the lowest amount in the exit layer of the back screen. In intensifying screens, where light absorption is not negligible, the light produced in these distant screen layers has the highest probability to be absorbed on its way towards the film emulsions. Light absorption will thus affect the light produced in a front screen to a higher degree than that produced in a back screen. If this is to be compensated for, the front screen should be made correspondingly thicker. The effect of light absorption may, therefore, be used as an argument for not making the back screen as thick as was theoretically predicted in Figure 6. It may even be taken as an argument for not making asymmetric screen pairs at all, as is the case with most of the screen pairs investigated.



## REFERENCES

Buchanan R.A., Finkelstein S.I. and Wickersheim K.A., 1972.

X-Ray exposure reduction using rare-earth oxysulphide intensifying screens.

Radiology 105:185-190.

Dick C.E. and Motz J.W., 1981.

Image information transfer properties of X-ray fluorescent screens.

Medical Physics 8(3):337-346.

Doi K., Vyborny C.J. and Holje G., 1982.

Development of a rigid fluorescent X-ray source for monoenergetic radiation studies in radiographic imaging.

Radiology 142:233-236.

Holje G., 1983 b.

Energy absorption in radiographic intensifying screens.

CODEN Report LUNFD6 (NFRA-3034) / LUMEDW (MERI-3034), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 c.

Sensitivity characteristics of radiographic screen-film systems.

CODEN Report LUNFD6 (NFRA-3035) / LUMEDW (MERI-3035), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 d.

Radiographic mottle in screen-film systems used in diagnostic radiology.

CODEN Report LUNFD6 (NFRA-3036) / LUMEDW (MERI-3036), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 e.

Energy absorption of fluorescent K X-rays produced in the phosphor layers of radiographic intensifying screens.

CODEN Report LUNFD6 (NFRA-3037) / LUMEDW (MERI-3037), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 f.

Coefficients for converting X-ray exposure to photon fluence and energy fluence.

CODEN Report LUNFD6 (NFRA-3038) / LUMEDW (MERI-3038), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G. and Svahn G., 1974.

Investigation of intensifying screens for X-ray cassettes (in Swedish, English summary).

The Swedish Institute for the Planning and Rationalization of Health and Social Welfare Services Report 6030:9.

Holje G., Svahn G., Hårdstedt C., Ramnhagen A., Öberg A. and Forsberg H., 1977.

Intensifying screens for X-ray cassettes, performance, usability, etc. (in Swedish, English summary).

The Swedish Institute for the Planning and Rationalization of Health and Social Welfare Services Publication S 67.

Holje G. and Doi K., 1982.

MTF's and Wiener spectra of radiographic screen-film systems. Part 2. Sensitivity, sensitometry, resolution and noise characteristics of new screen-film systems.

U.S. Department of Health and Human Services Publication FDA 82-8187, Bureau of Radiological Health, Rockville, Maryland 20857.

Stevels A.L.N. and Pingault F., 1975.

BaFCl:Eu<sup>2+</sup>, A new phosphor for X-ray intensifying screens.  
Philips Res. Reports 30:277-290.

Storm E. and Israel H.J., 1967.

Photon cross sections from 0.001 to 100 MeV for elements 1 through 100.

Los Alamos scientific laboratory of the University of California.  
LA-3753, U C-34, Physics, TID-4500.

Svahn G., 1977.

Diagnostic X-ray spectra. Doctoral thesis.

Dept. of Radiation Physics, University of Lund, Lund, Sweden.

Vyborny C.J., 1976.

The speed of radiographic screen film systems as a function of X-ray energy and its effect on radiographic contrast. Doctoral dissertation. The University of Chicago. Chicago, Illinois, U.S.A.

Wagner R.F., 1976.

Fast Fourier digital quantum mottle analysis with application to rare-earth intensifying screen systems.

Medical Physics 4(2):157-162.

Wagner R.F. and Weaver K.E., 1975.

Noise measurements on rare-earth intensifying screen systems.

SPIE Vol. 56, Medical X-ray Photo Optical Systems Evaluation.

Wagner R.F. and Weaver K.E., 1976.

Prospects of X-ray exposure reduction using rare-earth intensifying screens.

Radiology 118:180-188.

Dokumentutgivare  
Inst för radiofysik  
Handläggare  
Författare  
Gunnila Holje

Dokumentnamn  
CODEN Report  
Utgivningsdatum  
April 1983

Dokumentbeteckning  
3034  
Ärendebeteckning

Dokumenttitel o-h undertitel

ENERGY ABSORPTION IN RADIOGRAPHIC INTENSIFYING SCREENS

A study of energy absorption in intensifying screens with fluorescent layers of various chemical compositions under exposure conditions simulating those occurring in various diagnostic X-ray examinations.

Referat (sammandrag) The energy absorption of monoenergetic radiation is calculated from measured attenuation by employing tabulated mass attenuation coefficients. Photoelectric absorption alone is considered and the partial absorption of internally produced K X-rays is taken into account. The energy absorptions in the screens are also determined at twenty bremsstrahlung distributions, simulating those occurring in diagnostic X-ray examinations. The variations with radiation quality of the energy absorption in the intensifying screens form the basis for the predictions of image contrast. The influences of the screen thickness, the presence of scattered radiation, the chemical composition of the screen phosphor and the choice of X-ray tube potential on the image contrast are discussed. A comparison of the energy absorption versus the screens' thicknesses reveals the favourable energy absorption that exists at these radiation qualities in screens with barium, lanthanum or gadolinium as high Z element. This is shown to be a consequence of the high occurrence of K-shell interactions. A quantification of the absorbed K X-ray energy is made by relating the K X-ray absorption to the total energy absorption of incident photons. This ratio is expected to be applicable for predicting the influence of absorbed K X-ray energy on the quantum mottle and the resolution properties of the screen-film systems.

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Index-termer (ange källa)

SIS-  
DB 1  
DOKUMENTATABLAD enligt SIS 62:10 12

Omfång

Övriga bibliografiska uppgifter

Språk

Skriftsuppgifter

ISSN

ISBN

Dokumentet kan erhållas från

Mottagarens uppgifter

Inst för radiofysik vid Lunds universitet  
Lasarettet  
S-221 85 LUND

Preis

Blankett LU 11:25 1976-07





# ENERGY ABSORPTION IN RADIOGRAPHIC INTENSIFYING SCREENS

A study of energy absorption in intensifying screens with fluorescent layers of various chemical compositions under exposure conditions, simulating those occurring in various diagnostic x-ray examinations

Gunnilla Holje

Lund 1983



## CONTENTS.

Page

|     |                                                                                                                 |    |
|-----|-----------------------------------------------------------------------------------------------------------------|----|
| 1.  | INTRODUCTION.....                                                                                               | 1  |
| 2.  | CALCULATIONS OF ENERGY ABSORPTION IN INTENSIFYING SCREENS<br>FROM EXPERIMENTALLY DETERMINED ATTENUATION.....    | 5  |
| 2.1 | The mass attenuation and mass energy absorption<br>coefficients                                                 | 5  |
| 2.2 | Photon attenuation and energy absorption                                                                        | 5  |
| 2.3 | The dominating energy absorption processes                                                                      | 7  |
| 2.4 | Energy absorption of x-ray distributions                                                                        | 11 |
|     | * Reabsorbed K x-ray energy                                                                                     | 12 |
| 3.  | RESULTS AND DISCUSSION.....                                                                                     | 13 |
| 3.1 | Energy absorption at photon energies between<br>20 keV and 120 keV                                              | 13 |
| 3.2 | The energy absorption at the radiation quality pro-<br>duced at 80 kV filtered with 20 mm aluminium             | 16 |
|     | * Energy absorption versus screen thickness                                                                     | 18 |
|     | * Increases of screen thicknesses to attain increased<br>energy absorption and sensitivity                      | 20 |
|     | * Reabsorbed K x-ray energy                                                                                     | 22 |
| 3.3 | Mass energy absorption coefficients at the radiation<br>quality produced at 80 kV filtered with 20 mm aluminium | 24 |
|     | * The influence of screen thickness                                                                             | 24 |
|     | * The influence of the chemical composition of the<br>screen phosphor                                           | 26 |
| 3.4 | The energy absorption of x-ray distributions                                                                    | 27 |
|     | * Barium and Lanthanum screens                                                                                  | 27 |
|     | * Yttrium and Tungsten screens                                                                                  | 27 |
|     | * Gadolinium screens                                                                                            | 28 |
|     | * Gadolinium/Yttrium screens                                                                                    | 29 |
| 3.5 | Energy absorption characteristics - Image contrast                                                              | 29 |
|     | * The dependence on screen thickness                                                                            | 29 |

(cont.)

|                                                                       |    |
|-----------------------------------------------------------------------|----|
| * The dependence on the chemical composition of the screen phosphor   | 31 |
| * The dependence on choices of tube potential                         | 32 |
| 3.6 Reabsorbed K x-ray energy at various incident x-ray distributions | 32 |
| REFERENCES.....                                                       | 36 |

## 1. INTRODUCTION

The development of new x-ray phosphors (Buchanan et al., 1972; Stevels and Pingault, 1975) awakened renewed interest in the physical properties of radiographic screen-film systems. The new phosphors were shown to exhibit not only higher intrinsic efficiency (light-energy emitted per x-ray- or electron energy absorbed), but also higher x-ray energy absorption than conventional calcium tungstate phosphor in the energy range of interest in diagnostic radiology. The higher intrinsic efficiency of the new phosphors can lead to considerable increases in screen-film sensitivities, but at the cost of increased quantum mottle. The higher energy absorption in the new phosphors leads to more moderate increases in screen-film sensitivities but, which is important, not at the cost of increased quantum mottle (Holje, 1983 d). The impact of the improved energy absorption in the new phosphors is thus obvious.

Since the absorption characteristics of the new x-ray phosphors differ from those of calcium tungstate phosphor, the energy dependence of the sensitivity of the new screen-film systems can not be expected to be the same as that of conventional calcium tungstate systems. The implication of this is that the new systems may exhibit image contrast, sensitivity to scattered radiation and response to changes in x-ray tube potential, which are entirely different from those of calcium tungstate systems. By performing a detailed analysis of the absorption characteristics of the intensifying screens, it is possible to comprehend their sensitivity variations. Knowledge of absorption properties will also facilitate improvements in image quality and/or patient exposure by selecting appropriate screen-film systems in various diagnostic examinations.

Several reports have been published on the determinations of the energy absorption in intensifying screens. Since it is not a quantity which is easily measured or calculated, however, different approaches have been made in order to obtain an appropriate quantification of the energy absorption. Ludwig (1971) and Swank (1973) calculated the energy absorption from tabulated mass-energy absorption coefficients. Venema (1979) used the Monte Carlo simulation technique. Porter and Bril (1975) and Castle



(1977) performed experimental determinations and Vyborny (1976) made a semi-experimental approach in his determinations of energy absorption in intensifying screens.

An approach similar to that of Vyborny is employed in this investigation of the energy absorption in the intensifying screens, listed in Table 1. The energy absorption of monoenergetic radiation is calculated from measured attenuation (Holje, 1983 a), by employing tabulated mass-attenuation coefficients. Photoelectric absorption alone is considered, and the partial absorption of internally produced K x-rays is considered.

The energy absorptions in the screens are also determined at twenty bremsstrahlung distributions, simulating those occurring in different diagnostic x-ray examinations (Holje, 1983 f). The variations with radiation quality of the energy absorption in the intensifying screens form the basis for predictions of image contrast. The influences of the screen thickness, the presence of scattered radiation, the chemical composition of the screen phosphor and the choice of x-ray tube potential on the image contrast are discussed.

A comparison of the energy absorption versus the screens' thicknesses reveals the favourable energy absorption that exists at these radiation qualities in screens with barium, lanthanum or gadolinium as high Z-element. Their weighted mass-energy absorption coefficients are shown to amount to almost two times that of conventional calcium tungstate screens.

The high energy absorption in many of the new screens is shown to be an immediate consequence of the favourable location of the K-absorption edge of their high Z-element. The energy intervals where these phosphor screens have maximal energy absorption coincide well with those where many of the differential energy fluence distributions, as encountered in diagnostic radiology, are the highest. The high occurrence of K-shell interactions in these screens, however, leads to a high production of K x-rays. The consequent high absorption of K x-ray energy has been shown to be disadvantageous for the resolution properties (Karlsson et al., 1977; Arnold and Bjärngård, 1979). In spite of this unfavourable condition, the measured resolutions of the new screen-film systems are definitely superior

TABLE 1

| Manufacturer | Trade name        | Phosphor                                                                              | Dominating<br>K-abs/keV |
|--------------|-------------------|---------------------------------------------------------------------------------------|-------------------------|
| Agfa-Gevaert | M.R. 50           | LaOBr:Tb                                                                              | 38.93                   |
|              | M.R. 200          | "                                                                                     | "                       |
|              | M.R. 400          | "                                                                                     | "                       |
|              | M.R. 600          | "                                                                                     | "                       |
| CAWO         | SE 2              | LaOBr:Tb                                                                              | 38.93                   |
|              | SE 4              | "                                                                                     | "                       |
|              | SE 6              | "                                                                                     | "                       |
| DuPont       | Cronex Par Speed  | CaWO <sub>4</sub>                                                                     | 69.53                   |
|              | Cronex Quanta II  | BaFC1:Eu                                                                              | 37.44                   |
| Fuji         | Grenex G-4        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   |
|              | Grenex G-8        | "                                                                                     | "                       |
| General El.  | Blue Max 1        | LaOBr:Tb                                                                              | 38.93                   |
|              | Blue Max 2        | "                                                                                     | "                       |
| Ilford       | Rare Earth        | LaOBr:Tm                                                                              | 38.93                   |
| Kodak        | X-Omatic Regular  | BaSO <sub>4</sub> :Eu/SrSO <sub>4</sub> :Eu                                           | 37.44/16.11             |
|              | Lanex Fine        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   |
|              | Lanex Regular     | Gd <sub>2</sub> O <sub>2</sub> S:Tb/La <sub>2</sub> O <sub>2</sub> S:Tb <sup>1)</sup> | 50.24/38.93             |
| Philips      | Type 4360         | BaFC1:Eu                                                                              | 37.44                   |
|              | Type 6359         | "                                                                                     | "                       |
| Siemens      | Rubin Super       | CaWO <sub>4</sub>                                                                     | 69.53                   |
|              | Titan 923         | LaOBr:Tb                                                                              | 38.93                   |
| 3M           | Trimax Alpha 4    | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   |
|              | Trimax Alpha 8    | "                                                                                     | "                       |
| U.S. Radium  | Rarex BG Detail   | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>2)</sup>  | 50.24/17.04             |
|              | Rarex BG Mid Sp.  | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>3)</sup>  | 50.24/17.04             |
|              | Rarex BG High Sp. | "                                                                                     | "                       |
|              | Rarex B Mid Sp.   | Y <sub>2</sub> O <sub>2</sub> S:Tb                                                    | 17.04                   |

1) 93 %/7 % by weight 2) 60 %/40 % by weight 3) 75 %/25 % by weight

to those of conventional calcium tungstate systems with comparable sensitivity (Holje et al., 1977; Holje and Doi, 1982; Holje, 1983 g). Absorption of K x-rays, however, seems to be advantageous for the quantum mottle in screen-film systems (Vyborny et al., 1982). Aiming at a better understanding of its influence on the sensitivity, noise and resolution properties of screen-film systems, a quantification of K x-ray energy absorption will be made. The absorption of K x-ray energy will be related to the total energy absorption of incident photons in the screens. This ratio is expected to be applicable to predictions of the influence of absorbed K x-rays on the quantum mottle and the resolution properties of the screen-film systems.

## 2. CALCULATION OF ENERGY ABSORPTION IN THE INTENSIFYING SCREENS FROM EXPERIMENTALLY DETERMINED ATTENUATION.

### 2.1 The mass attenuation and mass energy absorption coefficients.

In the energy range of interest, the interactions between photons and phosphor materials take place as photoelectric effect, coherent scattering and Compton scattering. The total mass attenuation coefficient  $\mu/\rho$ , is therefore expressed as:

$$\mu/\rho = \tau/\rho + \sigma_{\text{coh}}/\rho + \sigma_{\text{c}}/\rho = \tau/\rho + \sigma_{\text{coh}}/\rho + \sigma_{\text{ca}}/\rho + \sigma_{\text{cs}}/\rho \quad (1)$$

and the mass energy absorption coefficient,  $\mu_{\text{en}}/\rho$ , is expressed as

$$\mu_{\text{en}}/\rho = \tau_{\text{a}}/\rho + \sigma_{\text{ca}}/\rho = \tau/\rho \cdot E/h\nu + \sigma_{\text{ca}}/\rho \quad (2)$$

where  $E$  is the average energy transferred to the medium per photoelectrically absorbed photon of energy  $h\nu$ .

By means of cross-section data published by Storm and Israel (1967), the mass attenuation coefficients were calculated for the various phosphor materials (Holje, 1983 e). These calculations indicate that energy is deposited predominantly as photoelectric absorption in all phosphor materials. The mass energy absorption coefficients can therefore be approximated to:

$$\mu_{\text{en}}/\rho \cong \tau_{\text{a}}/\rho = \tau/\rho \cdot E/h\nu \quad (3)$$

Mass-energy absorption coefficients expressed in this way are only slightly underestimated. The crudest approximation occurs at high photon energies in phosphors composed of low atomic number elements, such as  $\text{Y}_2\text{O}_2\text{S}$  and  $\text{LaOBr}$ , but even in these phosphors the underestimation is less than 2 % at 100 keV, and about 4 % at 120 keV. Since this investigation deals with the response to broad x-ray distributions, the resultant inaccuracy will be less than 2 %,

### 2.2 Photon attenuation and energy absorption.

Using the coefficients in Equations 1 and 2, the attenuation,  $A$ , and energy absorption,  $B$ , are written as:

$$A = 1 - e^{-\mu/\rho \cdot d} \quad (4)$$

$$B = 1 - e^{-\tau/\rho \cdot E/h\nu \cdot d} \quad (5)$$

From Equations 4 and 5 the energy absorption can be expressed as

$$B = A \frac{1 - e^{-\tau/\rho \cdot E/h\nu \cdot d}}{1 - e^{-\mu/\rho \cdot d}} \quad (6)$$

In the calculations, the first order approximations of the exponential expressions have been utilized (Vyborny, 1976). With these approximations, Equation 6 becomes:

$$B = A \cdot \frac{\tau/\rho}{\mu/\rho} \cdot E/h\nu \quad (7)$$

The attenuation, A, by the intensifying screens was experimentally determined at incident photon energies between 20 keV and 120 keV (Holje, 1983 a). The mass attenuation coefficients,  $\tau/\rho$ , and  $\mu/\rho$ , were determined for the phosphor materials at incident photon energies between 10 keV and 150 keV (Holje, 1983 e). - Being determined from the mass attenuation coefficients of the elements composing the phosphors, these composed mass attenuation coefficients will be denoted  $(\tau/\rho)_{\text{tot}}$  and  $(\mu/\rho)_{\text{tot}}$  in the following. - The factor E, the average energy deposited to the medium per photoelectrically absorbed photon of energy,  $h\nu$ , which changes character drastically at absorption edges in the phosphor materials, is treated in detail in Section 2.3.

Except for the fact that the expression in Equation 7 facilitates the calculations, it has the advantage over that in Equation 6 that it does not involve the screen thicknesses. Determinations of the screen thicknesses are, therefore, not necessary. The approximation, however, of the quotient in Equation 6, to yield that in Equation 7, is possible because of the comparable absolute values of the two exponents. The fractional overestimation introduced, by rejecting the higher order terms, is therefore only



somewhat smaller in the numerator than in the denominator, yielding a value of the approximated quotient, which is fairly close to the "true" value. The difference between the photoelectric mass absorption coefficients and the mass attenuation coefficient is particularly large at photon energies just exceeding that of the K-shell absorption edge in the high Z-element of the phosphor. The underestimation of the energy absorption here is the largest. When averaged according to the spectral distributions of photons of interest here, however, the resultant energy absorptions in the intensifying screens will not show any drastic underestimations. The underestimation of the energy absorption in screens made of yttrium oxysulphide or calcium tungstate phosphors is about -3 % when they are exposed to the radiation quality produced at 80 kV filtered with 20 mm aluminium. The corresponding underestimation in screens made of the other phosphors is about -10 %. This has not been considered crucial, since the primary intention of this investigation is not to evaluate physical properties of the intensifying screens in absolute terms. The objective is rather to provide measures, which can be employed to yield a reliable comparison in relative terms of physical properties of different intensifying screens.

### 2.3 The dominating energy absorption processes.

Due to the complex nature of E, some simplifications have been made to facilitate the calculations. All characteristic radiation produced in the phosphor materials, except for that produced in K-shell transitions in the highest atomic number element, is thus assumed to be totally absorbed. The energy deposited to the phosphor by these low energy x-rays is added to that deposited in the primary interaction event, and they are not regarded as separate deposition events. In these photoelectric interaction events, therefore, all incident photon energy is considered to be totally deposited in one event. These low energy x-rays consist of L x-rays of the highest Z-element and of K x-rays of the lower Z-elements of the phosphor. In phosphors with only one high Z-element, their mean free paths are of the order of the crystal size\* (Storm and Israel, 1967). These x-rays may, therefore, very well be treated as locally absorbed. Some phosphors, however, such as  $\text{LaOBr}$ ,  $\text{BaSO}_4/\text{SrSO}_4$  and  $\text{Gd}_2\text{O}_2\text{S}$  mixed with

\* Information about phosphor density and crystal size has been supplied by the manufacturers.

$\text{La}_2\text{O}_2\text{S}$  or  $\text{Y}_2\text{O}_2\text{S}$ , have two higher Z-elements. - In this context "higher Z" alludes to elements with K-absorption edges around 15 keV or higher.

- Here, not only the highest energy K x-rays, but also the second highest have a certain probability to escape from the phosphor. The assumption, that all but the highest energy K x-rays are locally reabsorbed, will, therefore, introduce some errors in the calculations. The energy absorptions in screens made of  $\text{LaOBr}$ ,  $\text{BaSO}_4/\text{SrSO}_4$  and  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$  are overestimated by only 1 %. The corresponding overestimation in the Lanex Regular screens made of  $\text{Gd}_2\text{O}_2\text{S}/\text{La}_2\text{O}_2\text{S}$  is as large as 4 %. This is not considered crucial, however, since only one screen-pair is concerned, and since the manufacturing of these mixed phosphor screens has ceased.

Based on the above assumption, all incident photon energy,  $h\nu$ , is deposited in photoelectric interactions involving photons with lower energies than that of the K-absorption edge,  $E_{\text{K-edge}}$  of the highest atomic number element of the phosphor material. Equation 7 is then:

$$B = A \cdot \frac{(\tau/\rho)_{\text{tot}}}{(\mu/\rho)_{\text{tot}}} \cdot E/h\nu \quad ; \quad E = h\nu \text{ for } h\nu < E_{\text{K-edge}} \quad (8)$$

At photon energies, higher than that of the K-absorption edge, the expression becomes more complex, since photoelectric interactions will result in a number of different energy depositions. Four different types of interactions are considered:

- (1) Firstly, in photoelectric interactions, other than those in the K-shell of the high Z-element, all incident photon energy is deposited in the phosphor material,  $E_1$  below.
- (2) All incident photon energy is also deposited in the phosphor material when interactions in the K-shell of the high Z-element are followed by emission of Auger electrons,  $E_2$  below.
- (3) When fluorescent K-shell interactions take place, all incident energy, which is not emitted as K x-ray energy, is assumed to be deposited in the phosphor material,  $E_3$  below.
- (4) The produced K x-ray energy,  $E_4$  below, may also contribute to the to-

tal energy absorption, since these x-rays have a certain probability to be reabsorbed (Shuping and Judy, 1977; Vyborny et al., 1978 and Holje, 1983 e). These secondary interaction events can take place at rather large distances from the primary interaction event. - The mean free paths of the K x-rays in  $\text{CaWO}_4$ -screens is 0.7 mm, in  $\text{LaOBr}$ -screens 0.2 mm, and in  $\text{Y}_2\text{O}_3$ -screens 0.1 mm. Those of the K x-rays in the other screens investigated are all 0.3 mm\* (Storm and Israel, 1967; Holje, 1983 a). Beyond these ranges, as many as 37 % of the emitted K x-rays are still expected to be attenuated. - The absorption of this secondary radiation is therefore treated as a separate absorption event. Further details, concerning the reabsorption of K x-rays, are discussed in connection to evaluations of noise properties of the screen-film systems (Holje, 1983 d).

The total energy absorption at incident photon energies higher than that of the K-absorption edge of the high Z-element is the sum of the four energy deposition events just described:

$$B = B_1 + B_2 + B_3 + B_4 \quad \text{for } h\nu \geq E_{K\text{-edge}} \quad (9)$$

where

$$B_1 = A \cdot \frac{(\tau/\rho)_{\text{tot}} - v \cdot (\tau/\rho)_{\text{h.a.}} \cdot \tau_K/\tau}{(\mu/\rho)_{\text{tot}}} \cdot E_1/h\nu ; E_1 = h\nu \quad (10)$$

$$B_2 = A \cdot \frac{v \cdot (\tau/\rho)_{\text{h.a.}} \cdot \tau_K/\tau}{(\mu/\rho)_{\text{tot}}} \cdot (1-\omega_K) \cdot E_2/h\nu ; E_2 = h\nu \quad (11)$$

$$B_3 = A \cdot \frac{v \cdot (\tau/\rho)_{\text{h.a.}} \cdot \tau_K/\tau}{(\mu/\rho)_{\text{tot}}} \cdot \omega_K \cdot E_3/h\nu ; E_3 = h\nu - \bar{E}_{K\text{-x-rays}} \quad (12)$$

$$B_4 = A \cdot \frac{v \cdot (\tau/\rho)_{\text{h.a.}} \cdot \tau_K/\tau}{(\mu/\rho)_{\text{tot}}} \cdot \omega_K \cdot B_K \cdot E_4/h\nu ; E_4 = \bar{E}_{K\text{-x-rays}} \quad (13)$$

\* Information about phosphor density has been supplied by the manufacturers.

where

|                             |                                                                                                   |
|-----------------------------|---------------------------------------------------------------------------------------------------|
| $(\tau/\rho)_{\text{tot}}$  | is the photoelectric mass attenuation coefficient of the phosphor                                 |
| $(\mu/\rho)_{\text{tot}}$   | is the mass attenuation coefficient of the phosphor                                               |
| $(\tau/\rho)_{\text{h.a.}}$ | is the photoelectric mass attenuation coefficient of the high Z-element of the phosphor,          |
| $\nu$                       | is the fraction by weight of the high Z-element,                                                  |
| $\tau_K/\tau$               | is the relative K-shell contribution to the photoelectric cross section (Storm and Israel, 1970), |
| $\omega_K$                  | is the K fluorescent yield,                                                                       |
| $\bar{E}_{K\text{-rays}}$   | is the weighted average of the K x-ray energies (Storm and Israel, 1970) and                      |
| $B_K$                       | is the probability that produced K x-ray energy is reabsorbed (Holje, 1983 e).                    |

Equations 9 through 13 can thus be simplified as:

$$B = A \cdot (S(h\nu) - T(h\nu) \cdot \omega_K \cdot \frac{\bar{E}_{K\text{-rays}}}{h\nu} \cdot (1-B_K)) ; h\nu \geq E_{K\text{-edge}} \quad (14)$$

$$S(h\nu) = \frac{(\tau/\rho)_{\text{tot}}}{(\mu/\rho)_{\text{tot}}} \quad (15)$$

$$T(h\nu) = \frac{\nu \cdot (\tau/\rho)_{\text{h.a.}} \cdot \tau_K/\tau}{(\mu/\rho)_{\text{tot}}} \quad (16)$$

The simplified expression in Equation 14 is sufficient for calculations of the total energy absorption. It gives, however, no indication about the relative contributions from the various energy absorption processes. Since these are needed for the determinations of noise equivalent absorption by the screens (Holje, 1983 d), the more complex expression in Equation 9 is employed. - Due to the expected influence of reabsorbed K x-ray

on noise and resolution properties of the screen-film systems, attention will be paid to the contribution from absorbed K x-ray energy to the total energy absorption. The factor  $B_4$  in Equation 13 will therefore be reported in the energy range of interest.

#### 2.4 Energy absorption of x-ray distributions.

The aim of this study is to determine the physical properties of screen-film systems when used in clinical situations, and the main interest is therefore focussed, not on their response to monoenergetic radiation, but on clinically relevant distributions. Information about the response to monoenergetic radiation is, however, important because it can easily be applied to broad spectral distributions to obtain the response to any x-ray spectrum.

The radiation qualities used in this investigation are those produced at the x-ray tube potentials 60, 80, 100 and 120 keV filtered with 5, 10, 15, 20 and 25 mm aluminium. These radiation qualities and their spectral distributions are described in detail elsewhere (Holje, 1983 f). By weighting the energy absorption of monoenergetic photons according to these energy fluence distributions, the energy absorption at the radiation qualities of current interest is achieved according to the relation:

$$B_{x,y} = \frac{\int_{h\nu \text{ min}}^{h\nu \text{ max}} B(h\nu) \cdot \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu \text{ min}}^{h\nu \text{ max}} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu} \quad (17)$$

where

$B_{x,y}$  is the energy absorption in the screens at the x-ray distribution produced at x kV filtered with y mm aluminium,

$B(h\nu)$  is the energy absorption of photons with energy  $h\nu$  and

$\left(\frac{d\Psi}{dh\nu}\right)_{x,y}$  is the differential energy fluence at x kV filtered with y mm aluminium

$h\nu \text{ min}$  and  $h\nu \text{ max}$  are the minimal and maximal photon energies.



Due to the large number of screens incorporated in the study, their energy absorption will be presented in a concise but still comprehensive, way. Absolute energy absorption values will therefore be given at only one radiation quality, namely at that produced at 80 kV filtered with 20 mm aluminium. The influence of the radiation quality on the energy absorption in all intensifying screens, with fluorescent layers of the same chemical composition, will be treated jointly and presented as normalized to the radiation quality of 80 kV and 20 mm aluminium. From data, presented in this way, information in absolute terms for all screen pairs investigated can be derived at the various radiation qualities.

Reabsorbed K x-ray energy. Many of the intensifying screens investigated have such chemical composition that the K-absorption energy of their high atomic number elements coincides well with the energy ranges covered by the various incident x-ray distributions. In this manner, K-shell interactions are utilized to provide optimal energy absorption conditions in the screens, and thus optimal sensitivity of the complete screen-film systems. In order to gain high sensitivity in the screen-film system, total absorption of the hereby produced characteristic radiation is desirable. If, on the other hand, high resolution of the screen-film system is to be attained, no absorption of the internally produced K x-rays should take place. This is due to the detrimental effect that they have on the resolution capacity, due to the fact that they can be absorbed at considerable distances from the initial interaction site (Karlsson et al., 1977; Arnold and Bjärngård, 1979). It is reasonable to believe that the larger the amount of reabsorbed K x-rays is in a screen-film system, the more serious will this detrimental effect become. An investigation is made here of the variation with radiation quality of the contributions of the K x-ray energy to the total energy absorbed in the screen-pairs:

$$\left(\frac{B_4}{B}\right)_{x,y} = \frac{\int_{h\nu \min}^{h\nu \max} B_4(h\nu) \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu \min}^{h\nu \max} B(h\nu) \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu} \quad (18)$$

This ratio is expected to be applicable for predictions of the variations with radiation quality of the resolution properties, MTFs, of the screen-film systems.

### 3. RESULTS AND DISCUSSION

#### 3.1 Energy absorption at photon energies between 20 keV and 120 keV.

Figures 1 to 7 illustrate the attenuation and energy absorption in seven intensifying screens, made of different phosphor materials. They also give the fraction of incident photon energy which is absorbed in the form of K x-ray energy, produced in the phosphor materials.

Figures 1 to 7 show that the energy absorption in the screens is only slightly lower than the attenuation, when the incident photon energy is lower than the K-absorption edge of the high Z-element. This difference is due to the escape of scattered radiation, produced in coherent and incoherent photon interactions. - The fact that incoherent absorption is excluded in the calculations of energy absorption is not expected to introduce any errors, since this absorption process is negligible at low photon energies (Holje, 1983 e). - The first order approximations, used in Equation 7, result in an underestimation by 3 % at the most of the energy absorption in the screens in this energy range of photons.

Figures 1 to 7 also illustrate the abrupt increases in attenuation and energy absorption which take place when the incident photon energy exceeds that of the K-absorption edge of the high Z-element. The energy absorption in the screens is here much lower than the attenuation. This is due to the escape of K x-rays, which are emitted subsequent to K-shell interactions. The probability for this characteristic radiation to be absorbed in the screens has been determined (Holje, 1983 e). The fraction of incident photon energy which is deposited in the screens by reabsorbed K x-rays is illustrated in Figures 1 to 7. The contribution of this secondary absorption (or reabsorption) process to the total energy absorption is considerable. At incident photon energies just exceeding that of the K-absorption edge, its contribution to the total energy absorption in these screens is between 25 % and 40 %. At higher energies, the fraction of incident photon energy which is transferred to K x-ray energy, is reduced, and the K x-ray contribution to the total energy absorption therefore decreases. The energy absorptions determined here agree within 2 % with those determined by Vyborny (1976) on comparable screens.

Attenuation, A, or Absorption, B

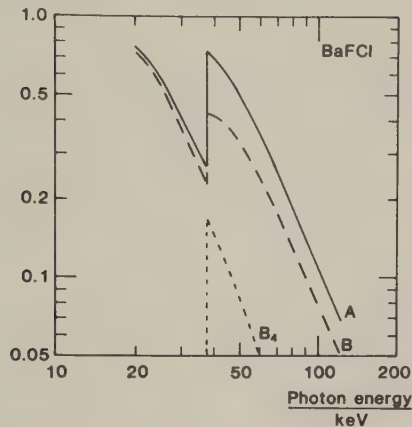


Figure 1. The attenuation and energy absorption of monoenergetic photons in Philips Type 4360 screens.  $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays.

Attenuation, A, or Absorption, B

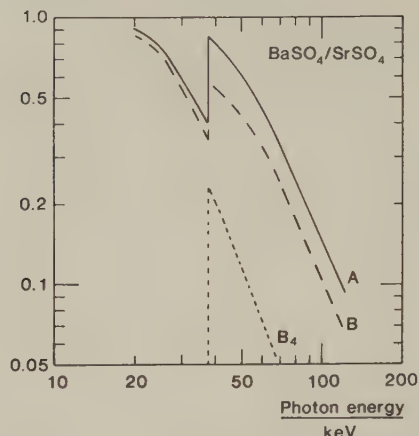


Figure 2. The attenuation and energy absorption of monoenergetic photons in X-Omatic Regular screens.  $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays.

Attenuation, A, or Absorption, B

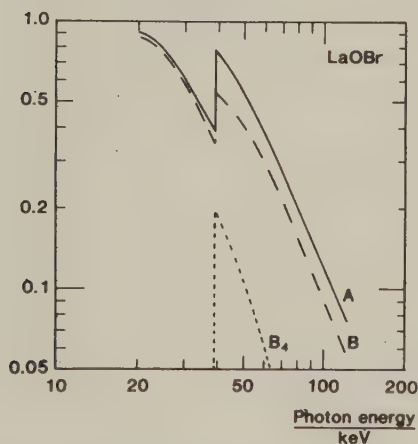


Figure 3. The attenuation and energy absorption of monoenergetic photons in M.R. 200 screens.  $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays.

Attenuation, A, or Absorption, B

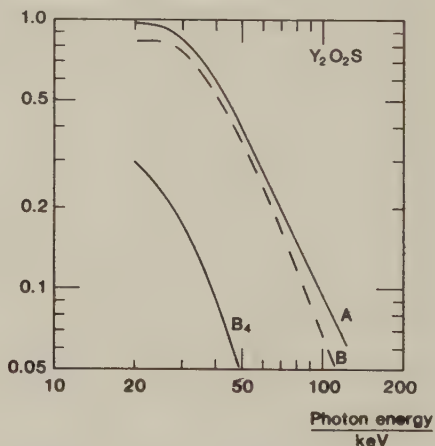


Figure 4. The attenuation and energy absorption of monoenergetic photons in Rarex B Mid Speed screens.  $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays.

Attenuation, A, or Absorption, B

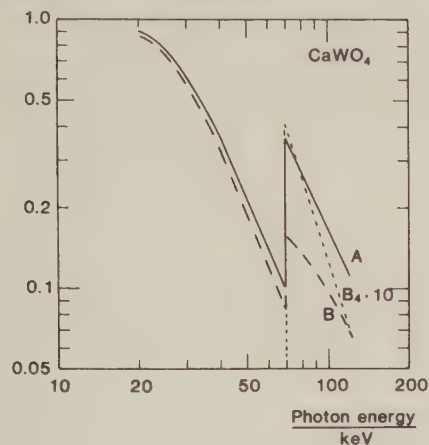


Figure 5. The attenuation and energy absorption of monoenergetic photons in Cronex Par Speed screens.  $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays.

Attenuation, A, or Absorption, B

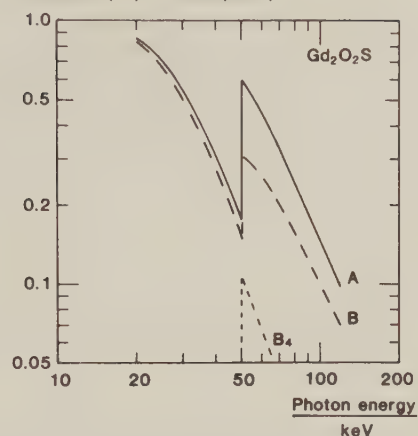


Figure 6. The attenuation and energy absorption of monoenergetic photons in Grenx G-4 screens.  $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays.

Attenuation, A, or Absorption, B

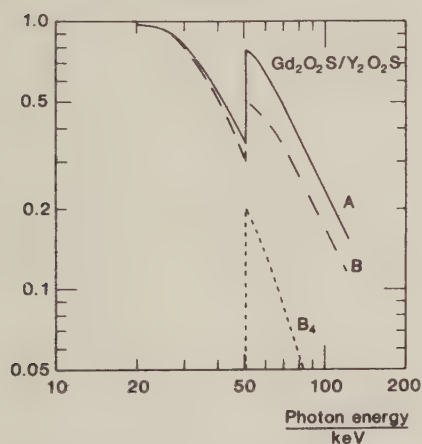


Figure 7. The attenuation and energy absorption of monoenergetic photons in Rarex BG Mid Speed screens.  $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays.

The exclusion of incoherent absorption in the calculations of energy absorption is not expected to introduce any significant errors, since this absorption process amounts to only a small percent of the total energy absorption at these higher photon energies. - The first order approximations, however, used to derive Equation 7, result in underestimations of the energy absorption, which can be substantial. At photon energies just above the K-absorption edges in the screens, presented in Figures 1 to 7, the underestimations are between 10 % and 20 %. These errors decrease rapidly as the photon energy increases, and the remaining underestimations at 100 keV are only 1-3 % in these screens.

### 3.2 The energy absorption at the radiation quality produced at 80 kV filtered with 20 mm aluminium filter.

Table 2, Column 2, presents the energy absorption in the various intensifying screens. This has been obtained, according to Equation 17, by weighting the energy absorption of monoenergetic photons according to the energy fluence distribution produced at 80 kV filtered with 20 mm aluminium.

In previous investigations (Holje et al., 1977, Holje and Doi, 1982), it was concluded that the M.R. screens, Blue Max screens and SE screens were essentially the same screens marketed under different names. This conclusion was based on the fact that the attenuation, sensitivity and resolution properties of the M.R. 200, Blue Max 1 and SE 2 screens were the same. Similar results were obtained for M.R. 400, Blue Max 2 and SE 4, as well as for M.R. 600 and SE 6 screens. For this reason, and since these screens will be modified in the near future, determinations of the energy absorption were only made on the M.R. screens. For practical purposes, the M.R. 200 data are expected to be applicable to the Blue Max 1 and SE 2 screens, the M.R. 400 data to be valid for the Blue Max 2 and SE 4 screens, and the M.R. 600 data to be valid for the SE 6 screens, as indicated in Table 2.

Table 2 shows that the energy absorption at 80 kV and 20 mm aluminium is between 0.24 and 0.50 in the new screens, whereas it is lower than 0.20 in the two pairs of calcium tungstate screens. In connection with the results of the attenuation measurements, it was mentioned that the attenuation in calcium tungstate screens of much higher sensitivity can be twice



TABLE 2

Physical properties of the intensifying screens at 80 kV and 20 mm Al

| Intensifying screens | Thickness*<br>g . cm <sup>-2</sup> | Energy<br>Abs. | Energy Abs.;K x-rays<br>Total Energy Abs. | ( $\mu_{en}/\rho$ )<br>cm <sup>2</sup> . g <sup>-1</sup> |
|----------------------|------------------------------------|----------------|-------------------------------------------|----------------------------------------------------------|
| M.R. 50              | 0.061                              | 0.26           | 0.21                                      | 4.94                                                     |
| M.R. 200             | 0.075                              | 0.31           | 0.23                                      | 4.95                                                     |
| M.R. 400             | 0.068                              | 0.28           | 0.22                                      | 4.83                                                     |
| M.R. 600             | 0.121                              | 0.43           | 0.26                                      | 4.65                                                     |
| SE 2                 |                                    | see M.R. 200   |                                           |                                                          |
| SE 4                 |                                    | see M.R. 400   |                                           |                                                          |
| SE 6                 |                                    | see M.R. 600   |                                           |                                                          |
| Blue Max 1           |                                    | see M.R. 200   |                                           |                                                          |
| Blue Max 2           |                                    | see M.R. 400   |                                           |                                                          |
| Rare Earth           | 0.103                              | 0.38           | 0.25                                      | 4.64                                                     |
| Titan 923            | 0.072                              | 0.29           | 0.22                                      | 4.76                                                     |
| Cronex Quanta II     | 0.084                              | 0.31           | 0.24                                      | 4.42                                                     |
| Type 4360            | 0.067                              | 0.26           | 0.22                                      | 4.49                                                     |
| Type 6359            | 0.097                              | 0.34           | 0.25                                      | 4.28                                                     |
| X-Omatic Regular     | 0.130                              | 0.35           | 0.24                                      | 3.31                                                     |
| Cronex Par Sp.       | 0.061                              | 0.16           | 0.032                                     | 2.86                                                     |
| Rubin Super          | 0.078                              | 0.19           | 0.037                                     | 2.70                                                     |
| Grenex G-4           | 0.082                              | 0.31           | 0.23                                      | 4.53                                                     |
| Grenex G-8           | 0.113                              | 0.39           | 0.25                                      | 4.37                                                     |
| Lanex Fine           | 0.070                              | 0.27           | 0.21                                      | 4.50                                                     |
| Lanex Regular        | 0.141                              | 0.47           | 0.26                                      | 4.50                                                     |
| Trimax Alpha 4       | 0.061                              | 0.24           | 0.20                                      | 4.50                                                     |
| Trimax Alpha 8       | 0.111                              | 0.39           | 0.25                                      | 4.45                                                     |
| Rarex BG Detail      | 0.081                              | 0.28           | 0.18                                      | 4.06                                                     |
| Rarex BG Mid Sp.     | 0.126                              | 0.41           | 0.24                                      | 4.19                                                     |
| Rarex BG High Sp.    | 0.167                              | 0.50           | 0.26                                      | 4.15                                                     |
| Rarex B Mid Sp.      | 0.124                              | 0.28           | 0.13                                      | 2.65                                                     |

\* (Holje, 1983 a)

as high as that in those investigated here (Holje, 1983 a). Because of this, one can also expect the energy absorption in very highly sensitive calcium tungstate screens to be a factor of two higher than that in the calcium tungstate screens reported here. This implies that the energy absorption in highly sensitive  $\text{CaWO}_4$ -screens can be as large as about 0.40, which is almost comparable to the value found in the new phosphor screens. From this comparison it is evident that the sensitivity gain of 2-4 times, achieved with the new screen-film systems, (Holje, 1983 c), is not only due to higher energy absorption, but must be partly accomplished by the higher light-yield of the new screens.

Energy absorption versus screen thickness. In Figure 8, the energy absorption at 80 kV filtered with 20 mm aluminium in the screen pairs is plotted versus their thicknesses (Holje, 1983 a). The three lines in Figure 8 are fitted by linear regression analysis to the data points of lanthanum oxybromide screens, gadolinium oxysulphide screens and calcium tungstate screens, respectively. This presentation gives a clear picture of the favourable energy absorption characteristics existing in most of the new phosphor screens. At this radiation quality, the energy absorption in these screens can exceed that of the calcium tungstate screens of equivalent thicknesses, by as much as a factor of 1.6.

The high energy absorption in screens with high atomic elements of lanthanum, barium or gadolinium is an immediate consequence of the favourable location of their K-absorption discontinuities. These are located between 37 and 55 keV. The energy intervals where these phosphor screens have maximal energy absorptions, therefore, coincide well with those where the incident differential energy fluence is highest. The photon distribution produced at 80 kV filtered with 20 mm aluminium, can be approximated to a triangular distribution ranging from 30 keV to 80 keV, with peak emission half-way between (Holje, 1983 f).

Calcium tungstate screens have increased energy absorption, due to the commencement of K-shell interactions at about 70 keV. This is at the high energy part of the energy interval covered by the incident photon distribution. These screens have their lowest energy absorption at energies where the incident differential energy fluence is highest. The low weighted energy absorption in these screens is a result of this poor adaption

Absorption

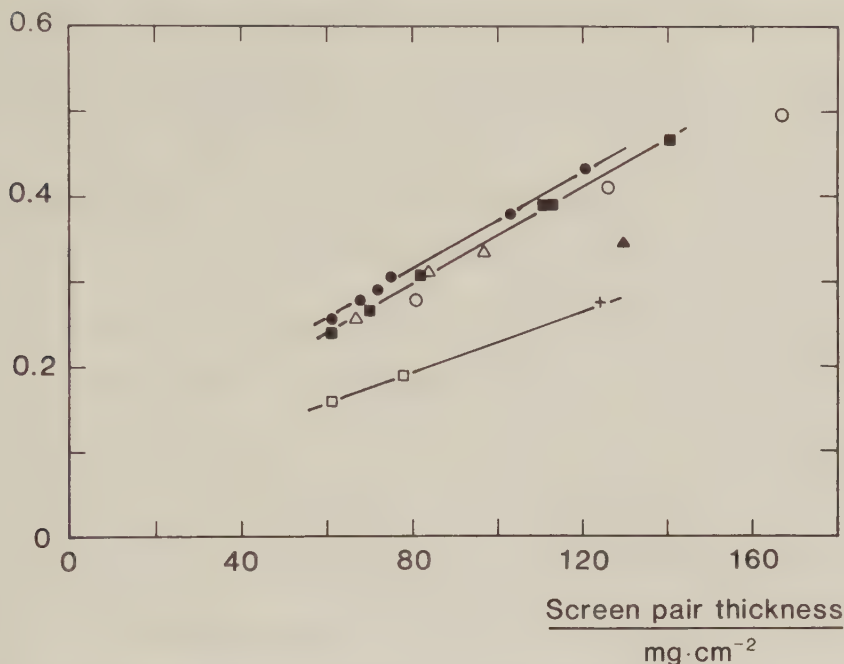


Figure 8. The energy absorptions in the screen pairs at 80 kV filtered with 20 mm aluminium versus their thicknesses.  
 +:  $\text{Y}_2\text{O}_2\text{S}$ -screens,  $\Delta$ :  $\text{BaFCl}$ -screens,  $\blacktriangle$ :  $\text{BaSO}_4/\text{SrSO}_4$ -screens,  $\bullet$ :  $\text{LaOBr}$ -screens  
 $\blacksquare$ :  $\text{Gd}_2\text{O}_2\text{S}$ -screens,  $\circ$ :  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ -screens,  $\square$ :  $\text{CaWO}_4$ -screens. The lines are fitted by linear regression analysis to the values for  $\text{LaOBr}$ -screens,  $\text{Gd}_2\text{O}_2\text{S}$ -screens and  $\text{CaWO}_4$ -screens, respectively.

of the incident energy fluence distribution to their energy absorption characteristics.

According to Figure 8, the weighted energy absorption in the yttrium oxy-sulphide screens is comparable to that in calcium tungstate screens. Their K-shell discontinuity at about 17 keV is well below the energy interval covered by the incident energy fluence of photons. The continuously decreasing energy absorption in these screens has great similarities to that of the calcium tungstate screens in the energy interval of interest. The resultant effect is the same, i.e. low energy absorption when exposed to this energy fluence distribution.

The high capacity of the new screens to absorb energy will also be maintained when other radiation distributions are employed, Figure 10. The higher energy absorption at equal thickness is one of the reasons why new screen-film combinations can provide much higher sensitivity than the

calcium-tungstate systems, with the same or better image quality (Holje and Doi, 1982).

Increases of screen thicknesses to attain increased energy absorption and sensitivity. An important finding is that none of the screen pairs investigated absorb more than about 50 % of the incident x-ray energy at 80 kV filtered with 20 mm aluminium. It, therefore, appears to be possible to achieve further sensitivity gains by simply making the screens thicker, so that they would absorb a greater amount of the incident radiation. Due to the exponential characteristic of x-ray absorption, however, the increase in screen thickness has to be relatively large. Since the thickest screens seen today absorb approximately 50 % of the radiation energy, it will be necessary to make "new" highly sensitive screens four times thicker to absorb 94 % and five times thicker to absorb 97 % of the incident radiation energy. Since an increase in screen thickness introduces an additional light absorption, the increase in sensitivity will not be as large as one might expect from the increase in absorption. Any prediction about the sensitivity gain, resulting from an increase of x-ray absorption, therefore, gives only the upper limit of that which is possible to reach.

The highest sensitivity obtained with screens incorporated in this study was obtained with the M.R. 600 screens (Holje, 1983 c). Their sensitivity is 7.5 times higher than that of the conventional medium sensitive calcium tungstate screens, Cronex Par Speed, and yet their energy absorption is only 0.43. If these screens were made thick enough to absorb all incident x-ray energy, their highest obtainable sensitivity would be increased to about 17 times that of the Cronex Par Speed system.

Concerning potential sensitivity increase, the Rarex B Mid Speed system is even more promising. Its sensitivity is 5.4 times that of the Cronex Par Speed system, and the energy absorption is as low as 0.28. If these screens were to absorb all incident x-ray energy, a sensitivity gain of almost 20 times the Cronex Par Speed sensitivity would be obtained. The thickness of these theoretical screens, however, must be about ten times higher than that of the original B Mid Speed screens, and light absorption can therefore be considerable. This will in turn make the sensitivity gain less than that predicted, but it will also cause less deterioration of the



resolution than would be the case in completely light transparent screens. Since it is not possible, at present, to accurately predict the relationship between sensitivity and resolution and the effect of screen thickness on these properties, the only reliable method is an experimental evaluation of test screens.

Even though screens with total absorption are hypothetical, it is of interest to discuss the possibility of constructing screens with very high absorption. It has been shown (Holje, 1983 a) that asymmetric construction of screen pairs becomes more important the higher their absorption is. In a symmetric screen pair which absorbs 96 % of the incident x-ray energy, 80 % will be absorbed in the front screen. In this extreme case, it is obvious that the second screen, i.e. the back screen, is of minor importance, and that a single screen system would be a good alternative. Due to light scatter and absorption in the screen material, single screen systems should always be exposed in "back screen" geometry, so that most of the light is produced close to the film. If the light absorption is large in the screen pair described above, a single "back screen" system may have higher sensitivity than the system with two screens.

If the two screens in the pair, absorbing 96 % of incident energy, on the other hand, were to absorb equal amounts of x-ray energy, the separate energy absorption in the front screen and the back screen should be 0.48 and 0.92 respectively. The thickness of the back screen has to be almost four times that of the front screen. Only one-fifth of the total screen thickness should thus be given to the front screens. Now, since energy absorption in the screen pair is 0.96 and the energy absorption in the single back screen is 0.92, it is again obvious that the use of a front screen is quite ineffective and probably unnecessary.

One advantage with single screen systems over screen pair systems is that a single-emulsion film can be used. Cross-over exposure, that exists in double-emulsion film, is hereby eliminated. Its degrading effect on the resolution has been described in the literature (Rossmann, 1962; Sander-son and Cleare, 1974; Doi et al., 1981). In an attempt to reduce cross-over exposures, Kodak has introduced the X-Omatic Regular and Fine screens, emitting ultra-violet light, which has low probability to penetrate the film base. 3 M has developed low cross-over exposure film, XUD, by means



of anti-halation coatings between the emulsion layers and the film base. Systems with one screen and single-emulsion film are at present used for purposes that require ultra fine resolution, such as mammography. No manufacturer has thus far chosen this latter alternative for conventional radiography. It may, however, be realized when intensifying screens with higher energy absorption are to be developed. - High energy absorption and low light-yield are favourable when low noise levels are needed (Holje, 1983 d). -

Reabsorbed K x-ray energy. Table 2, Column 3, presents the contribution of K x-ray energy to the total energy absorption, Equation 18, in the various intensifying screens at 80 kV filtered with 20 mm. The reabsorbed K x-ray energy amounts to less than 4 % of the total energy absorption in the calcium tungstate screens, but to between 13 % and 26 % in the new screens. The low contribution in the former screens is mainly due to the fact that very few photons in an 80 kV bremsstrahlung spectrum have energies exceeding that of the K-absorption edge of tungsten at 69.53 keV, and consequently very few K x-rays are produced. In addition, the mean free path of tungsten K x-rays is considerable in this phosphor, approximately six times the actual screen thicknesses, and therefore the probability for their escape is high (Holje, 1983 e).

Among the new screens, it is interesting to note that those made of yttrium oxysulphide phosphor have the lowest K x-ray energy contribution to the total energy absorbed by the screens. This may seem surprising, since the K-shell absorption energy in yttrium, at 17.04 keV, is lower than the lowest energy of this incident spectral distribution of photons. Consequently, all incident photons have a possibility to interact with K-shell electrons of yttrium. The fluorescent yield in yttrium is, however, relatively low, 0.69, compared with approximately 0.90 in the high Z-elements of the other phosphor materials. This brings the production of K x-rays down. Once they are produced, however, they have a very high probability to be absorbed in the screen material. It has been shown (Holje, 1983 e) that 74 % of the produced K x-ray energy is absorbed in these yttrium oxysulphide screens. Of importance, however, is that only a small fraction of the incident photon energy is deposited in the medium in such a reabsorption process of 15 keV K x-rays. Only 15 keV/50 keV =

30 % of the energy of an incident 50 keV photon, for example, is deposited when such an absorption event take place.

The contribution of internally produced K x-ray energy to the energy absorption of monoenergetic photons has been determined in five 100 mg/cm<sup>2</sup> thick screens of different phosphor materials (Holje, 1983 e). Guided by the monoenergetic responses, it is possible to grossly interpret the responses, when the screens are exposed to the photon distribution of immediate interest here. So, for example, the fraction of energy absorbed through reabsorption of K x-rays in Y<sub>2</sub>O<sub>2</sub>S-screens, has already at 30 keV, decreased to one-half of its value at the K-absorption edge, which is almost 45 %. The most influential energy interval in Y<sub>2</sub>O<sub>2</sub>S-screens will, therefore, not be involved, when these screens are exposed to the photon distribution produced at 80 kV and 20 mm aluminium filter. At photon energies above 38.39 keV, the monoenergetic responses in BaFCl- and LaOBr-screens are about twice as high as that in Y<sub>2</sub>O<sub>2</sub>S-screens. Having this background, it is understandable that the contribution of K x-ray energy to the total energy absorption in the M.R. 600 screens, (121 mg/cm<sup>2</sup>) made of LaOBr, is twice as high as that in the Rarex B Mid Speed screens, (124 mg/cm<sup>2</sup>) made of Y<sub>2</sub>O<sub>2</sub>S, according to Table 2. At photon energies higher than 50 keV, the fraction of energy absorption through reabsorbed K x-rays is highest in Gd<sub>2</sub>O<sub>2</sub>S-screens. The energy interval with the highest monoenergetic response in these screens coincides well with that of the maximal photon emission of the 80 kV x-ray spectrum. This agreement between the response of Gd<sub>2</sub>O<sub>2</sub>S-systems and the distribution of incident photons outweighs the lack of K absorption below 50 keV to such an extent that their fractional K x-ray absorption becomes comparable to that in lanthanum and barium screens. Table 2 shows that the K x-ray contribution to the total energy absorbed in Grenex G-8 screens (113 mg/cm<sup>2</sup>) and Lanex Regular screens (141 mg/cm<sup>2</sup>), made of Gd<sub>2</sub>O<sub>2</sub>S, is equal to that in the earlier mentioned LaOBr-screens, M.R. 600.

Table 2 also illustrates that the contribution of reabsorbed K x-ray energy to the total energy absorption increases with increasing screen thickness. This is expected, since internally produced x-rays have lower probability of escaping from thick screens. In the thick screen pairs discussed above, the absorbed K x-ray energy amounts to as much as 25 % of the total absorbed energy. This considerable contribution of secondary radia-

tion may be surprising for persons who are used to work with the conventional calcium tungstate systems, which have much lower contribution of K x-ray energy to the totally absorbed energy.

### 3.3 Mass energy absorption coefficients at the radiation quality produced at 80 kV filtered with 20 mm aluminium.

The mass energy absorption coefficient is an important quantity, since it expresses a pure physical property of the screen phosphor, which, at least in the monoenergetic case is not dependent upon the thickness of the absorbing layer. Since data are available on the energy absorptions,  $B_{80,20}$ , and the thicknesses,  $d$ , (Table 2, Columns 1 and 2) of the various screen pairs, the efficient or weighted mass energy absorption coefficients at 80 kV filtered with 20 mm aluminium can be determined according to the following expression:

$$(\mu_{en}/\rho)_{80,20} = - \frac{\ln(1-B_{80,20})}{d} \quad (19)$$

The weighted mass energy absorption coefficient was determined using data on all of the screen pairs investigated. These are listed in Table 2, Column 4 and it is evident that screens made of the same phosphor material have somewhat different weighted mass energy absorption coefficients.

The influence of screen thickness. Since screens with the same chemical composition have different thicknesses, they will distort the incident distributions of photons to various degrees. Photons with the greatest probability of being absorbed by the screen material are absorbed in the first screen layer, leaving a beam of photons which have lower probability of being absorbed. This implies, in terms of weighted mass energy absorption coefficients, that there is a steady decrease from the entrance layer throughout the entire screen thickness. When weighted mass energy absorption coefficients are determined as here, as an average for the entire screen thickness, the thick screens can thus be expected to adopt lower values than thin screens, although they have identical chemical compositions. This is demonstrated in the figure where the weighted mass energy absorption coefficients of the screens are plotted versus the screen thicknesses. The three lines in figure 9 are fitted by linear regression analysis to the data-points of lanthanum oxybromide screens, barium fluoro-

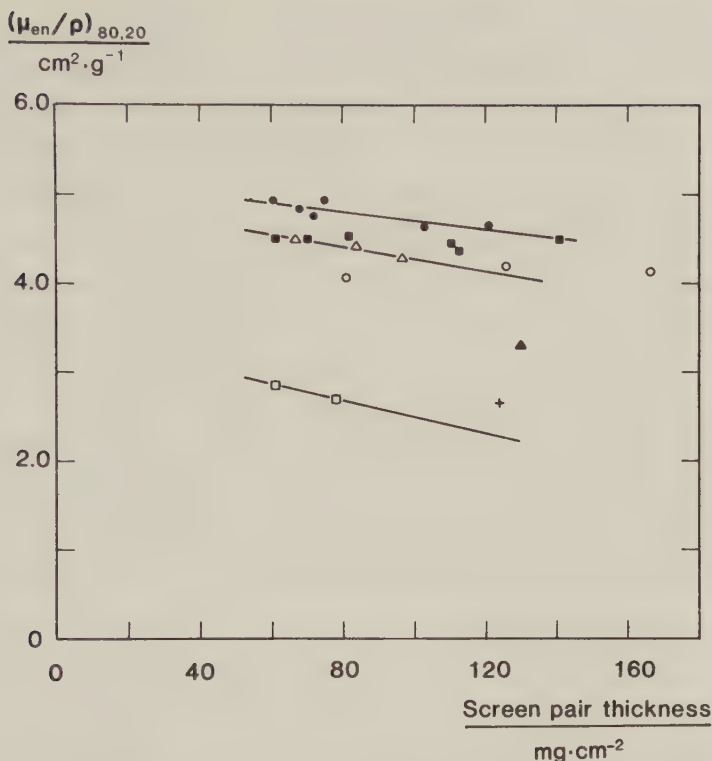


Figure 9. Weighted mass energy absorption coefficients of the phosphor screens at 80 kV filtered with 20 mm aluminium versus their thicknesses. +:  $\text{Y}_2\text{O}_2\text{S}$ -screens,  $\Delta$ :  $\text{BaFCl}$ -screens,  $\blacktriangle$ :  $\text{BaSO}_4/\text{SrSO}_4$ -screens,  $\bullet$ :  $\text{LaOBr}$ -screens,  $\blacksquare$ :  $\text{Gd}_2\text{O}_2\text{S}$ -screens,  $\circ$ :  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ -screens,  $\square$ :  $\text{CaWO}_4$ -screens. The lines are fitted by linear regression analysis to the values for  $\text{LaOBr}$ -screens,  $\text{BaFCl}$ -screens and  $\text{CaWO}_4$ -screens, respectively.

chloride screens and calcium tungstate screens, respectively. These are drawn to indicate the established inverse relationship between screen thickness and weighted mass energy absorption coefficient. No similar relationship was, however, observed for screens composed of gadolinium oxysulphide phosphor. Taking into consideration that the difference in weighted mass energy absorption coefficients found between thin and thick screens of the other phosphors only amounts to a few percent this may not seem surprising. In addition, the approximation in Equation 7, which has been used in the determinations of the energy absorption, has given rise to some of the observed decreases in Figure 9. It is obvious, therefore, that more accurate determinations have to be performed in order to exactly reveal such subtle details as the dependence on the weighted mass



energy absorption coefficient of the screen thickness.

The influence of the chemical composition of the screen phosphor. Figure 9 gives a clear picture of the differences in weighted mass energy absorption coefficients for screens made of different phosphors. At this radiation quality, the weighted mass energy absorption coefficients for screens made of lanthanum oxybromide are found to be slightly greater than those for the other rare earth screens. No distinction can be made between barium fluorochloride screens, gadolinium oxysulphide screens and screens made of a mixture of gadolinium oxysulphide and yttrium oxysulphide. The weighted mass energy absorption coefficients for these screens are between 1.6 and 1.9 times higher than those for the calcium tungstate screens. It is apparent from Figure 9 that the calcium tungstate screens and yttrium oxysulphide screens have the lowest weighted mass energy absorption coefficients of all of the screens investigated. The barium sulphate/strontium sulphate screens are only slightly better in this regard.

The high weighted mass energy coefficients for most of the new screens are an immediate consequence of the favourable matchings existing between the mass energy absorption coefficients for these phosphors and the distribution of the incident energy fluence (cf. the previous section, dealing with the weighted energy absorptions in screens of different thicknesses and chemical compositions).

Data in Figure 9 establish that the mass energy absorption coefficients, weighted according to the energy fluence distribution produced at 80 kV filtered with 20 mm aluminium, are low in screens whose energy absorption characteristics are dominated by a low Z-element like yttrium ( $Z=39$ ), or by a high Z-element like tungsten ( $Z=74$ ). The largest weighted mass energy absorption coefficients are found in screens with high Z-element of atomic numbers lying between these two extremes. This is shown by the high weighted mass energy absorption coefficients found for screens with high Z-elements of lanthanum ( $Z=56$ ), barium ( $Z=57$ ), or gadolinium ( $Z=64$ ). Since this radiation quality simulates that existing behind 25 cm human tissue (Holje, 1983 f) when exposed at the x-ray tube potential 80 kV, one can conclude that the latter screens are the better x-ray energy absorbers, as used in many clinical examinations.



### 3.4 The energy absorption of x-ray distributions.

The weighted energy absorption as expressed in Equation 17, in the intensifying screens at various radiation qualities is illustrated in Figure 10. The radiation qualities are produced at 60, 80, 100 and 120 kV filtered with 5 to 25 mm aluminium (Holje, 1983 f). Data are presented relative to those at 80 kV filtered with 20 mm aluminium. Intensifying screens made of identical phosphor materials are treated as one group, and indications are given for the energy absorption in the thinnest and thickest screens in each group. Due to their similar absorption properties, screens made of BaFCl and BaSO<sub>4</sub>/SrSO<sub>4</sub> are presented together.

Barium- and Lanthanum screens. The weighted energy absorption characteristics in screens made with barium (Z=56) or lanthanum (Z=57) as high atomic number elements are very similar. These similarities are a direct consequence of their almost identical attenuation properties (Holje, 1983 a).

Compared to the weighted attenuation, the weighted energy absorption exhibits slightly larger variations with changes in radiation quality. These discrepancies can mainly be explained by the escape of characteristic radiation produced in the screen material. The attenuation and energy absorption of monoenergetic photons, illustrated in Figures 2 to 4, showed that the K-shell discontinuity of energy absorption is smaller, due to K x-ray escape, than that of attenuation. When exposed to broad x-ray distributions, K-shell discontinuities have been found to have a smoothing effect on the screen responses (Holje, 1983 a). In the case of weighted attenuation and energy absorption in barium and lanthanum screens, it is obvious that the larger the discontinuity, the greater the smoothing effect.

Yttrium and tungsten screens. It should be noted in Figure 10 that Y<sub>2</sub>O<sub>2</sub>S-screens and CaWO<sub>4</sub>-screens have similar energy dependences at 60 and 80 kV.

In the energy range of interest here, 20 keV to 120 keV, the energy absorption in Y<sub>2</sub>O<sub>2</sub>S-screens decreases regularly with increasing photon energy. Since there is no K-absorption discontinuity to average out their response variation when exposed to different x-ray distributions, these screens exhibit the largest variation in weighted energy absorption at

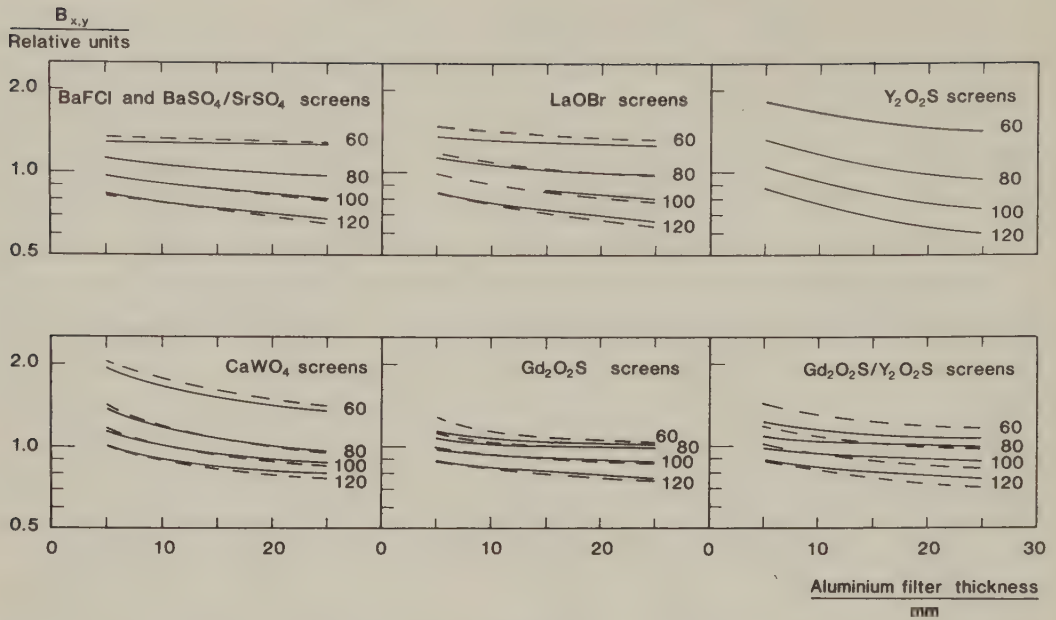


Figure 10. Energy absorption in intensifying screens of different chemical composition at various incident radiation distributions relative to that at 80 kV filtered with 20 mm aluminium.  $x$  denotes x-ray tube potential and  $y$  denotes the aluminium filter thickness used to produce these radiation distributions.

all of the radiation qualities studied here.

The K-absorption discontinuity in  $\text{CaWO}_4$ -screens appears in the upper energy region of several of these x-ray distributions. With only a minor absorption discontinuity involved, or none at all, when exposed to 60 and 80 kV x-ray spectra, the  $\text{CaWO}_4$ -screens exhibit energy absorption properties very similar to those of  $\text{Y}_2\text{O}_2\text{S}$ -screens. When  $\text{CaWO}_4$ -screens are exposed to 100 kV and 120 kV spectra. K-shell absorption in tungsten has a remarkable smoothing effect on the weighted energy absorption. Due to K x-ray escape, causing a shallower discontinuity, these variations are greater than those found for the weighted attenuation, (Holje, 1983 a).

Gadolinium-screens. These screens have less variations in their weighted energy absorption than any of the other phosphor screens studied. The K absorption discontinuity of gadolinium at about 50 keV is efficiently coordinated to the photon distributions employed, which gives this flat response. Their weighted attenuation was even less dependent on radiation

quality, (Holje, 1983 a). This again shows how the escape of inherently produced K x-ray energy disturbs the flat response variation that exists for the weighted attenuation. The higher production of K x-rays at 100 kV compared to 60 kV causes a larger fraction of incident energy to escape as K x-ray energy. This explains why the weighted energy absorption is lower at 100 kV than at 60 kV, although the weighted attenuation adopts equal values at these two tube potentials (Holje, 1983 a).

Gadolinium/Yttrium screens. These screens have slightly larger variations in weighted energy absorption than pure gadolinium oxysulphide screens. This is due to the characteristics of the yttrium oxysulphide part of the screens, which previously was shown to have the largest variation in energy response of all of the screens investigated.

The large difference between the responses of thin and thick screens within this group is merely due to their different composition of the two phosphor materials (cf. Holje, 1983 a). The Rarex BG Detail screens have the largest content of yttrium oxysulphide: 40 % compared to only 25 % in the other two screen pairs. These circumstances, combined with the fact that this screen pair is the thinnest, result in the relatively large variation in weighted energy absorption among these screens as shown in Figure 10.

### 3.5 Energy absorption characteristics - Image contrast.

The dependence on screen thickness. Data in Figure 10 indicate that screen thickness has a minor influence on the energy absorption characteristics. A 15 % difference at the most is found in the weighted energy absorption among LaOBr-screens and  $Gd_2O_2S$ -screens, which can differ by as much as a factor of two in thickness. A clear tendency is seen, however, towards thin screens having a more pronounced energy dependence.

Since a system's sensitivity characteristic is mainly determined by its energy absorption characteristic (Vyborny, 1976; Holje, 1983 c), this latter parameter's dependence on radiation quality is an important property, which affects the final image contrast. The difference in energy absorptions between thin and thick screens, illustrated in Figure 10, can therefore be expected to lead to differences in the image contrast. To understand its effect on the contrast, data on the energy dependence in

## Film density

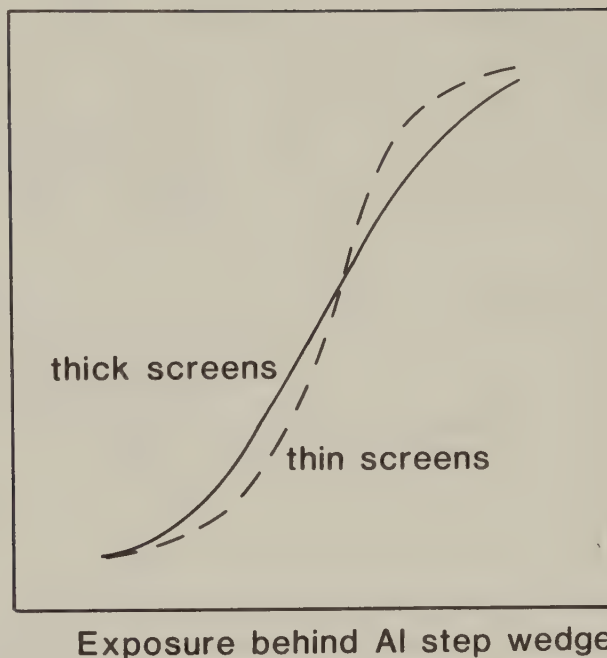


Figure 11. Contrast. H&D-curves produced with thin and thick screens using an aluminium step-wedge.

Figure 10 are presented in a simple way in Figure 11. It is here assumed that "pseudo-H&D curves"\* have been produced with one thin and one thick screen pair, using an aluminium step-wedge. From Figure 11 it is clearly seen that the thin screen pair, with its relatively higher energy absorption at low aluminium filtration (or equivalent to low energetic radiation), gives the steepest density gradient. This implies that, if only the primary radiation produced light exposing the film, thin screens would give high contrast images.

The presence of scattered radiation, however, emanating from the objects, could produce the opposite results, because thin screens are more sensitive to this low energetic radiation. Since the ratio of scattered-to-primary radiation is influenced by many factors, such as object thickness,

\* These are called pseudo-H&D curves because they are not only the system's responses to an increase in x-ray exposure, but also to a change in radiation quality. Especially when x-ray phosphors with different energy response are available, this combined effect, achieved when using a step-wedge to produce H&D curves can be misleading.



field size, grid-ratio, high tension, filter, geometry, etc., it would be almost impossible to predict the resultant effect of the high sensitivity to low energetic radiation existing in thin screens.

Experimental investigations (Nielsen, 1982) have indicated that thin screens can produce lower contrast images when they are exposed to clinically relevant mixtures of primary and scattered radiation. This means that the amount of scattered radiation in this case is so high, that it destroys their ability to produce images with higher contrast than those produced with thick screens.

The dependence on the chemical composition of the screen phosphor. Figure 10 shows, in an illustrative way, that different phosphor materials have different energy responses. Previous discussions, concerning the differences in energy response and the resultant image contrast provided by thin and thick screens, are also valid for the differences in energy response, which are caused by the different chemical compositions of the phosphor materials. If primary radiation only exposes the screen-film system,  $\text{Y}_2\text{O}_2\text{S}$ -screens with the highest relative energy absorption of low energetic radiation would, thus, give the highest image contrast, and  $\text{Gd}_2\text{O}_2\text{S}$ -screens the lowest. The high sensitivity to low energetic radiation of  $\text{Y}_2\text{O}_2\text{S}$ -screens, however, increases their sensitivity to scattered radiation, which reduces their image contrast. It is difficult to predict whether  $\text{Y}_2\text{O}_2\text{S}$ -screens and  $\text{Gd}_2\text{O}_2\text{S}$ -screens would give greater image contrast in clinical situations, since the ratio of scattered-to-primary radiation is influenced by many factors, as mentioned previously.

It may well be that some phosphor screens give the highest contrast in a certain clinical situation, but not in another. In spite of the fact that  $\text{Y}_2\text{O}_2\text{S}$ -screens give the highest contrast in the absence of scattered radiation, their high energy absorption of low energetic radiation is a serious drawback. Since scattered radiation does not transfer any diagnostic information, but only reduces the image quality, the ideal recording system would be a system which is sensitive only to transmitted primary radiation and not to scattered radiation. With this aspect laid on an ideal system, screens made of  $\text{Gd}_2\text{O}_2\text{S}$  are to be preferred (Castle, 1977) and in situations where their image contrast is not high enough, improvements in the contrast of the x-ray pattern can be done by using



lower x-ray tube potential.

The dependence on choices of tube potential. The choice of tube potential to obtain appropriate image contrast in various diagnostic examinations has been established during the years when  $\text{CaWO}_4$  was used, almost exclusively, as the phosphor material of intensifying screens. The differences in the energy responses of various phosphor materials, shown in Figure 10, however, indicate that one specific tube potential may not give the same contrast with screens made of different phosphors. When switching from conventional  $\text{CaWO}_4$ -screens to new screen-film systems, one must be aware of the fact that it might be necessary to make changes in the tube potential to maintain the image contrast. It was mentioned previously that the image contrast is heavily affected by the ratio of primary-to-scattered radiation. Since this may differ drastically between different radiological examinations, patient thicknesses and choices of equipment, it is very difficult to theoretically predict the image contrast in individual situations. The most accurate method is, therefore, to analyse the image contrast in the practical situation. Too low image contrast should then be compensated for by a decrease of x-ray tube potential and too high contrast by an increase of tube potential. - Some of the confusion, which arose when the new screens were introduced, was caused by their different energy dependence, which resulted in image contrasts different from those obtained with  $\text{CaWO}_4$ -systems.

### 3.6 Reabsorbed K x-ray energy at various incident x-ray distributions.

A comprehensive study of the contribution of K x-ray energy to the total absorbed energy at various radiation qualities is presented in Figure 12. All of the data are normalized to those at 80 kV and 20 mm aluminium filter, which are listed in Table 2. The intensifying screens are presented in groups according to the chemical composition of their fluorescent layers. Data on the thinnest and thickest screen pairs in each group are presented. In addition to the twenty radiation qualities treated so far, that at 80 kV without any extra filter has been incorporated for the analysis related to the resolution properties (Holje and Doi, 1982).

Figure 12 shows that quite different radiation quality responses are obtained in screens made of the different phosphor materials. The contribution of K x-rays to the total energy absorbed in calcium tungstate

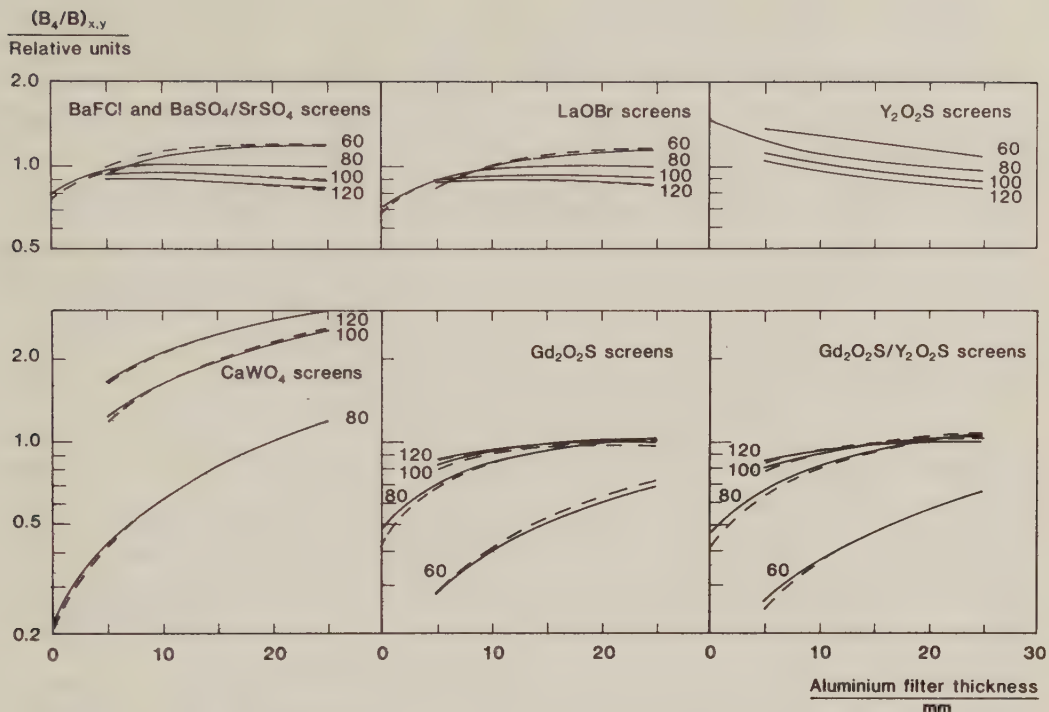


Figure 12. The contribution of K x-ray energy to the total absorbed energy in screens of different chemical composition at various incident radiation distributions relative to that at 80 kV filtered with 20 mm aluminium.  $x$  denotes the x-ray tube potential and  $y$  the aluminium filter thickness used to produce these radiation distributions.

screens increases with increased aluminium filter thickness or x-ray tube potential. In yttrium oxysulphide screens, the K x-ray contribution decreases with increased filter thickness or tube potential, while the responses in screens with high  $Z$ -elements of barium, lanthanum or gadolinium adopt an intermediate position. This difference in responses is a consequence of the different K-absorption energies of the high  $Z$ -elements of these phosphors.

When exposed to monoenergetic radiation, the production of K x-ray energy and its subsequent absorption begins abruptly, when the incident photon energy becomes just high enough for K-shell interactions. As the incident photon energy increases above this level, the fraction of incident energy which is transferred to K x-ray energy gradually decreases. This results in a continuously decreasing contribution of K x-ray energy to the total energy absorbed, (Holje, 1983 e). The x-ray distributions employed here

are made to contain larger fractions of high energy photons, either through reduction of low energy photons by increasing the aluminium filter thickness, or through the addition of high energy photons by increasing the x-ray tube potential. When broad x-ray distributions are employed, the monoenergetic response of the screens is smoothed out, but the fundamental process remains. The result of this smoothing is that there will be a gradual increase up to a saturation level of the K x-ray contribution to the energy absorbed when the filter thickness or tube potential is increased. Once this level is reached, further increases of either one of these two parameters will result in decreased response. The energy range covered by the photon distributions used here, however, is not large enough to show this complete behaviour in only one group of phosphor screens. It can, however, be illustrated by the combined responses of phosphor screens with high Z-elements of decreasing atomic number. The gradual increase of the K x-ray contribution to the energy absorbed is shown in the calcium tungstate screens ( $E_{K-edge} = 69.53 \text{ keV}$ ), where the response increases with increased aluminium filter thickness or x-ray tube potential. The saturation level is seen in screens with gadolinium as the high Z-element ( $E_{K-edge} = 50.24 \text{ keV}$ ). Their response reaches a level where it is almost independent of changes in aluminium filter thickness or tube potential. A decrease in response is seen in screens with a high Z-element of barium or lanthanum ( $E_{K-edge} = 37.44 \text{ and } 38.93 \text{ keV}$ ). The decrease with increased aluminium filter thickness, however, is seen only at the higher x-ray tube potentials. In yttrium oxysulphide screens, finally, ( $E_{K-edge} = 17.04 \text{ keV}$ ) the K x-ray contribution to the absorbed energy decreases continuously with increased aluminium filter thickness or x-ray tube potentials.

The energy absorption characteristics, including the contribution from reabsorbed K x-ray energy, is determinant for the variations with radiation quality of the sensitivity, noise and resolution properties of screen-film systems. This has been treated in other publications (Holje, 1983 c, d; Holje and Doi, 1982). It is shown in Figures 10 and 12, that energy absorption properties are strongly dependent on the chemical composition of the fluorescent layer of the screens. From this it is evident that the physical properties of screen-film systems should be evaluated

at appropriate radiation qualities. To compile data, which are applicable to all clinical situations, is, however, an unrealistic task. Experimentally determined physical properties of screen-film systems at some radiation qualities, therefore, often have to be supplemented by predictions in order to yield data, which are appropriate in specific radiological examinations. It has been shown (Holje and Doi, 1982) that the energy absorption properties evaluated in this investigation are useful in such predictions.

## REFERENCES

Arnold B.A. and Bjärngard B.E., 1979.

The effect of phosphor K X-rays on the MTF of rare-earth screens.  
Medical Physics 6(6):500-503.

Buchanan R.A., Finkelstein S.I. and Wickersheim K.A., 1972.

X-Ray exposure reduction using rare-earth oxysulfide intensifying screens.  
Radiology 105:185-190.

Castle J.W., 1977.

Sensitivity of radiographic screens to scattered radiation and its relationship to image contrast.  
Radiology 122:805-809.

Doi K., Loo L.N., McDowell Anderson T. and Frank P.H., 1981.

Effect of crossover exposure on radiographic image quality of screen-film systems.  
Radiology 139:707-714.

Holje G., 1983 a.

Photon attenuation by radiographic intensifying screens.  
CODEN Report LUNFD6 (NFRA-3033) / LUMEDW (MERI-3033), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 c.

Sensitivity characteristics of radiographic screen-film systems.  
CODEN Report LUNFD6 (NFRA-3035) / LUMEDW (MERI-3035), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 d.

Radiographic mottle in screen-film systems used in diagnostic radiology.  
CODEN Report LUNFD6 (NFRA-3036) / LUMEDW (MERI-3036), Dept. of Radiation Physics, Lund University, Lund, Sweden.



Holje G., 1983 e.

Energy absorption of fluorescent K X-rays produced in the phosphor layers of radiographic intensifying screens.

CODEN Report LUNFD6 (NFRA-3037) / LUMEDW (MERI-3037), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 f.

Coefficients for converting X-ray exposure to photon fluence and energy fluence.

CODEN Report LUNFD6 (NFRA-3038) / LUMEDW (MERI-3038), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 g.

Physical properties of radiographic screen-film systems. Doctoral thesis. Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., Svahn S., Hårdstedt C., Ramnhagen A., Öberg A. and Forsberg H., 1977.

Intensifying screens for X-ray cassettes, performance, usability, etc. (in Swedish, English summary).

The Swedish Institute for the Planning and Rationalization of Health and Social Welfare Services Publication S 67.

Holje G. and Doi K., 1982.

MTF's and Wiener spectra of radiographic screen-film systems. Part 2. Sensitivity, sensitometry, resolution and noise characteristics of new screen-film systems.

U.S. Department of Health and Human Services Publication FDA 82-8187, Bureau of Radiological Health, Rockville, Maryland 20857.

Karlsson M., Wickman G. and Hettinger G., 1977.

Characteristics of X-ray screen phosphor at photon energies between 20 - 140 keV.

Paper presented at the 9th Nordic Meeting of Clinical Physics, Gothenburg, Sweden.

Ludwig G.W., 1971.

X-Ray efficiency of powder phosphors.

Journal of the Electrochemical Society 118(7):1152-1159.

Nielsen B., 1982.

Personal communication.

Porter J.A. and Bril A., 1975.

Absolute X-ray efficiencies of some phosphors.

Journal of the Electrochemical Society 122(8):1086-1088.

Rossmann K., 1962.

Modulation transfer function of radiographic systems using fluorescent screens.

Journal of the Optical Society of America 52(7):774-777.

Sanderson G.K. and Cleare H.M., 1974.

MTF of screen-film systems: The influence of screens and crossover.

Photographic Science and Engineering 18(3):251-253.

Shuping R.E. and Judy P.E., 1977.

Energy absorbed in calcium tungstate X-ray screens.

Medical Physics 4(3):239-243.

Stevens A.L.N. and Pingault F., 1975.

BaFCl:Eu<sup>2+</sup>, A new phosphor for X-ray intensifying screens.

Philips Research Reports 30:277-290.

Storm E. and Israel H.J., 1967.

Photon cross sections from 0.001 to 100 MeV for elements 1 through 100.

Los Alamos scientific laboratory of the University of California,  
LA-3753, U C-34, Physics, TID-4500.

Storm E. and Israel H.J., 1970.

Photon cross sections from 1 keV to 100 MeV for elements Z = 1 to Z = 100.

Nuclear Data Tables 7(6):565-588.

Swank R.K., 1973.

Absorption and noise in X-ray phosphors.

Journal of Applied Physics 44(9):4199-4203.

Venema H.W., 1979.

X-Ray absorption, speed and luminescent efficiency of rare-earth and other intensifying screens.

Radiology 130:765-771.

Vyborny C.J., 1976.

The speed of radiographic screen-film systems as a function of X-ray energy and its effect on radiographic contrast. Doctoral dissertation. The University of Chicago, Chicago, Illinois, U.S.A.

Vyborny C.J., Metz C.E., Doi K. and Haus A.G., 1978.

Calculated characteristic X-ray reabsorption in radiographic screens. Journal of Applied Photographic Engineering 4:172-177.

Vyborny C.J., Loo L.N. and Doi K., 1982.

The energy-dependent behaviour of noise Wiener spectra in their low-frequency limits: Comparison with simple theory.

Radiology 144(3):619-622.



Dokumentutgivare  
Inst för radiofysik  
Händläggare

Dokumentnamn  
CODEN Report  
Utgivningsdatum  
April 1983

Dokumentbeteckning  
3035  
Ärendebeteckning

Författare  
Gunnilla Holje

Dokumenttitel och undertitel

SENSITIVITY CHARACTERISTICS OF RADIOGRAPHIC SCREEN-FILM SYSTEMS

A study of the sensitivity and its correlation to the energy absorption in intensifying screens with fluorescent layers of various chemical compositions. An evaluation at a broad range of radiation distributions, simulating those transmitted through the object in various diagnostic X-ray examinations.

Referat (sammandrag) A comprehensive analysis of the sensitivity characteristics of radiographic screen-film systems has been performed. The study incorporates 27 screen-film systems with seven different phosphor compositions. Their sensitivities are determined at twenty bremsstrahlung distributions, simulating those occurring in various diagnostic X-ray examinations. A comparison in absolute terms of the sensitivities of the systems is made at the radiation quality produced at 80 kV filtered with 20 mm aluminium. The energy deposited per unit screen-area for the production of film density 1.0, which is determined from energy absorption and sensitivity properties, is found to be independent of the radiation qualities studied here. The relationship between sensitivity- and energy absorption characteristics is established. It is shown that the characterization of screen-film sensitivity in terms of reciprocal X-ray exposure may be misleading when interpreting the energy dependence of screen-film sensitivity. Indicators of the light-yield of the screen-film systems are determined. These are employed in a comprehensive demonstration of the relationship between light-yield, energy absorption and sensitivity of the screen-film systems. The balance between energy absorption and light-yield to attain a specific sensitivity is utilized for predicting the ultimate image quality.

Förslag till ytterligare nyckelord:

Klassifikationssystem och -klasser 1

Indextermor (ange källa)

Omfång

Övriga bibliografiska uppgifter

Språk

Sekretessuppgifter

ISSN

ISBN

Dokumentet kan erhållas från

Medtagarens uppgifter

Inst för radiofysik vid Lunds universitet  
Lasarettet  
S-221 85 LUND

Pris

S-S  
DB 1

DOCUMENTDATABLAD enligt SIS 62 10 12

Blankett LU 11:25 1976-07





# SENSITIVITY CHARACTERISTICS OF RADIOGRAPHIC SCREEN-FILM SYSTEMS

A study of the sensitivity and its correlation to the energy absorption in intensifying screens with fluorescent layers of various chemical compositions. An evaluation at a broad range of radiation distributions, simulating those transmitted through the object in various diagnostic x-ray examinations

Gunnila Holje

Lund 1983



## CONTENTS.

|                                                                                                                                                  | Page |
|--------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 1. INTRODUCTION.....                                                                                                                             | 1    |
| 2. EXPERIMENTAL PROCEDURE.....                                                                                                                   | 4    |
| 2.1 The exposure conditions                                                                                                                      | 4    |
| 2.2 Radiation quality response of the ionization chamber                                                                                         | 6    |
| 2.3 Exposure rate - Reciprocity law failure of the film                                                                                          | 8    |
| 3. RESULTS AND DISCUSSION.....                                                                                                                   | 10   |
| 3.1 Screen-film sensitivities at the radiation quality produced at 80 kV filtered with 20 mm aluminium                                           | 10   |
| 3.2 The energy deposited per unit screen area to produce film density 1.0                                                                        | 12   |
| * The radiation quality dependence                                                                                                               | 13   |
| * The energy deposited per unit area of the screen-screen-film systems                                                                           | 15   |
| 3.3 Screen-film sensitivities; their dependence on radiation quality                                                                             | 16   |
| * Relative sensitivities expressed as relative reciprocal energy fluences                                                                        | 16   |
| * The relationship between relative sensitivity and relative energy absorption                                                                   | 17   |
| * Adjustments of x-ray exposure to obtain correct film density                                                                                   | 19   |
| * Relative sensitivities expressed as relative reciprocal x-ray exposures                                                                        | 20   |
| * The risk for misinterpretation of the radiation quality dependence of the sensitivity, when expressed in terms of relative reciprocal exposure | 21   |
| 3.4 Relative light-yield of screen-film systems                                                                                                  | 23   |
| * Intrinsic efficiency and light-yield                                                                                                           | 23   |
| * The relative light-yields of the screen-film systems                                                                                           | 25   |

(cont.)

|                 |                                                                           |    |
|-----------------|---------------------------------------------------------------------------|----|
| 3.5             | Sensitivity, the balance between energy absorption and light-yield        | 27 |
| *               | Sensitivity, energy absorption and light-yield of the screen-film systems | 27 |
| *               | Sensitivity, light-yield and expected quantum noise                       | 28 |
| REFERENCES..... |                                                                           | 31 |



## 1. INTRODUCTION

The development of new x-ray phosphors with higher x-ray energy-to-light energy conversion efficiency than that of conventional calcium tungstate phosphor (Buchanan et al., 1972; Stevels and Pingault, 1975) initiated a production of more efficient x-ray intensifying screens. The high energy conversion efficiency of the new phosphors, which is achieved partly by increased intrinsic efficiency (light-energy emitted per x-ray- or electron energy absorbed) and partly by increased energy absorption in the energy range of interest in diagnostic radiology, made it possible to improve screen-film sensitivity without any increase in screen thickness. This is important, since thick screens in general have less capacity to provide high resolution. The higher intrinsic efficiency of the new phosphors can lead to considerable increases in screen-film sensitivities, but at the cost of increased quantum mottle. The higher energy absorption in the new phosphors leads to more moderate increases in screen-film sensitivities but, which is important, not at the cost of increased quantum mottle (Holje, 1983 d). It is thus obvious that it is of vital importance for the ultimate image quality whether a sensitivity increase is attained through increased energy absorption or through increased light-yield of the screens (light-energy emitted from the screen surface, which is directed towards the film per unit of x-ray energy absorbed).

Due to their different energy absorption characteristics, the contrast, sensitivity to scattered radiation (Castle, 1977) and response to changes in x-ray tube potential of the new screen-film systems can be entirely different from those of conventional calcium tungstate systems. Analysis of the energy dependence of the sensitivity of the screen-film systems will make it possible to reveal such differences. Since the main interest in the past has been focussed on the sensitivity increase which can be attained with the new screen-film systems, the majority of the reports deal with the sensitivity of new screen-film systems compared to that of

conventional calcium tungstate systems at different x-ray tube potentials (Rossi et al., 1976; Reynolds et al., 1976; Venema, 1979). Analysis of sensitivity variations with object thickness is, however, more relevant for image contrast predictions (Holje et al., 1977).

A basic investigation has been reported by Vyborny et al. (1977). These authors studied the dependence of screen-film sensitivity on photon energy by use of nearly monoenergetic x-rays emitted by a filtered fluorescent source. This investigation exactly reveals the relationship between incident photon energy and screen-film sensitivity. The sensitivity was found (Vyborny, 1976) to be almost directly related to the energy absorption in the screens at the various photon energies. A similar relationship has been established for broad x-ray distributions (Venema, 1979).

A comprehensive analysis of the sensitivity characteristics of radiographic screen-film systems has been performed in this investigation. The study incorporates twenty-seven screen-film systems with seven different phosphor compositions. Their sensitivities, expressed as the reciprocal of the energy fluences which are needed to give a net film density of 1.0, are determined at twenty bremsstrahlung distributions, simulating those occurring in different diagnostic x-ray examinations (Holje, 1983 f). Comparison in absolute terms of the sensitivities of the various systems is made at the radiation quality produced at 80 kV filtered with 20 mm aluminium.

Knowledge of the energy absorption in the screens (Holje, 1983 b) and the sensitivity of the screen-film systems enables determinations of the energy deposited per unit screen area for production of a film density of 1.0. This is found to be independent of the radiation qualities studied here, which is in agreement with the findings of Shuping and Judy (1977).

The relationship between sensitivity- and energy absorption characteristics is established. In this context, it is pointed out that the characterization of screen-film sensitivity in terms of reciprocal x-ray exposure, which is frequently seen, is confusing and may be misleading when interpreting the energy dependence of screen-film sensitivity.

Indicators of the light-yields of the screen-film systems are determined. These are employed in a comprehensive demonstration of the relationship between light-yield, energy absorption and sensitivity of the screen-film systems investigated. The balance between energy absorption and light-yield to attain a specific screen-film sensitivity is utilized for prediction of the ultimate image quality.

## 2. EXPERIMENTAL PROCEDURE.

### 2.1 The exposure conditions.

The screen-film systems incorporated in this study are listed in Table 1. This table also indicates that Kodak RP 14 film (at present called Kodak X-Omatic RP) was used for screens emitting ultra-violet and/or blue light, and Kodak Ortho G film for screens emitting green light. The screen-film systems were enclosed in evacuated plastic bags and exposed in free-air geometry to minimize backscatter. After exposure, the films were developed with Kodak RP X-Omat developer for 28 s and at 34°C.

The x-ray generator used in the evaluations of the screen-film sensitivities was a 12-pulse coupled 3-phase generator (Svahn, 1977). The radiation qualities were produced at 60 kV to 120 kV with 5 mm to 15 mm aluminium filter (Holje, 1983 f). The HVL's of the radiation behind 5-25 mm aluminium are the same as those behind 6.25 - 31.25 cm of tissue in this high tension range. Scattered radiation from the aluminium filter was excluded from the measurements by using a large distance between the aluminium filter and the screen-film systems.

The sensitivities of the screen-film systems were determined as the reciprocal energy fluence, which is needed to produce the net film density 1.0. This was evaluated from characteristics curves, H&D-curves of the screen-film systems at the various x-ray distributions.

The H&D - curves were produced in a transverse time-scale sensitometer, where the screen-film systems were moved stepwise into exposure position. The x-ray exposure conditions, i.e. x-ray tube potential, tube current and exposure times, were identical for all separate exposures made for one complete H&D-curve. Density increases on the film were obtained by increasing the number of such identical x-ray exposures. The first strip, the lowest film density, corresponds to one x-ray exposure, the second strip to two exposures etc... All x-ray exposures were monitored by a transmission ionization chamber, mounted on the collimator of the x-ray tube. The corresponding x-ray exposures of the screen-film systems were determined by means of an ionization chamber, which was calibrated using

TABLE 1.

| Manufac-<br>turer | Trade name        | Phosphor                                                                              | Dominating<br>K-abs/keV | Film |
|-------------------|-------------------|---------------------------------------------------------------------------------------|-------------------------|------|
| Agfa-<br>Gevaert  | M.R. 50           | LaOBr:Tb                                                                              | 38.93                   | XRP  |
|                   | M.R. 200          | "                                                                                     | "                       | "    |
|                   | M.R. 400          | "                                                                                     | "                       | "    |
|                   | M.R. 600          | "                                                                                     | "                       | "    |
| CAWO              | SE 2              | LaOBr:Tb                                                                              | 38.93                   | XRP  |
|                   | SE 4              | "                                                                                     | "                       | "    |
|                   | SE 6              | "                                                                                     | "                       | "    |
| DuPont            | Cronex Par Sp.    | CaWO <sub>4</sub>                                                                     | 69.53                   | XRP  |
|                   | Cronex Quanta II  | BaFCl:Eu                                                                              | 37.44                   | "    |
| Fuji              | Grenex G-4        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   | OG   |
|                   | Grenex G-8        | "                                                                                     | "                       | "    |
| G.E.              | Blue Max 1        | LaOBr:Tb                                                                              | 38.93                   | XRP  |
|                   | Blue Max 2        | "                                                                                     | "                       | "    |
| Ilford            | Rare Earth        | LaOBr:Tm                                                                              | 38.93                   | XRP  |
| Kodak             | X-Omatic Reg.     | BaSO <sub>4</sub> :Eu/SrSO <sub>4</sub> :Eu                                           | 37.44/16.11             | XRP  |
|                   | Lanex Fine        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   | OG   |
|                   | Lanex Reg.        | Gd <sub>2</sub> O <sub>2</sub> S:Tb/La <sub>2</sub> O <sub>2</sub> S:Tb <sup>1)</sup> | 50.24/38.93             | "    |
| Philips           | Type 4360         | BaFCl:Eu                                                                              | 37.44                   | XRP  |
|                   | Type 6359         | "                                                                                     | "                       | "    |
| Siemens           | Rubin Super       | CaWO <sub>4</sub>                                                                     | 69.53                   | XRP  |
|                   | Titan 923         | LaOBr:Tb                                                                              | 38.93                   | "    |
| 3M                | Trimax Alpha 4    | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   | OG   |
|                   | Trimax Alpha 8    | "                                                                                     | "                       | "    |
| U.S.<br>Radium    | Rarex BG Detail   | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>2)</sup>  | 50.24/17.04             | OG   |
|                   | Rarex BG Mid Sp.  | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>3)</sup>  | 50.24/17.04             | "    |
|                   | Rarex BG High Sp. | "                                                                                     | "                       | "    |
|                   | Rarex B Mid Sp.   | Y <sub>2</sub> O <sub>2</sub> S:Tb                                                    | 17.04                   | XRP  |

The films are manufactured by Eastman Kodak Co.

1) 93 %/ 7 % by weight 2) 60 %/ 40 % by weight, 3) 75 %/ 25 % by weight.



a Swedish substandard ionization chamber (see below). The film densities were measured by using a McBeth TD 504 densitometer.

## 2.2 Radiation quality response of the ionization chamber.

The x-ray exposures were measured with an E.I.L. (Electronic Instruments Limited) dosimeter, Model 37 C, supplied with a 35 cm<sup>3</sup> air-equivalent ionization chamber, E.I.L. Model A37A. The radiation quality response of a typical Model A37A ionization chamber is shown in Figure 1. It varies about 4 % over the range of energies for which it is designed, i.e. 35-120 kV with low filtration, 1.0 - 4.0 mm Al HVL (E.I.L., 1965). The manufacturer emphasizes that application of correction factors is necessary, when the ionization chamber is used outside this energy-range.

The E.I.L. ionization chamber was calibrated using a Swedish substandard ionization chamber, Shonka No 131, with known response to radiation qualities ranging from 0.9 up to 17.2 mm Al in HVL<sub>X</sub>, i.e. HVL determined by exposure measurements. Since the principal interest in the past has been focussed on radiation distributions used for radiation therapy, these HVLs are produced with high tube potentials and low filtrations. These radiation distributions are different from those which reach the image recording media in diagnostic radiology. In order to avoid oversimplification of the definition of radiation quality, the concept of HVL should be used with caution. Figure 1, showing the measured calibration functions for the E.I.L. ionization chamber, is an illustrative example of the limitations of the HVL concept. Here various HVL<sub>X</sub>s, expressed in mm Al, have been produced at four different x-ray tube potentials (60, 80, 100, 120 kV) by varying the aluminium filter thickness. - The conversions from x-ray distributions to exposure HVLs were made by use of tabulated data, (Mika and Reiss, 1973). - Most of these HVL<sub>X</sub>s are represented by more than one, sometimes as many as four, different radiation distributions and it is obvious from Figure 1 that this E.I.L. ionization chamber does not have any unique response to the various radiation qualities, when they are specified by the concept HVL. According to Figure 1, the different radiation distributions, yielding the same HVL<sub>X</sub>s in the range of 4 to 6 mm Al, lead to calibration factors which may differ by 10 %.

Exposure calibration factor  
 $\text{mR} \cdot (\text{scale division})^{-1}$

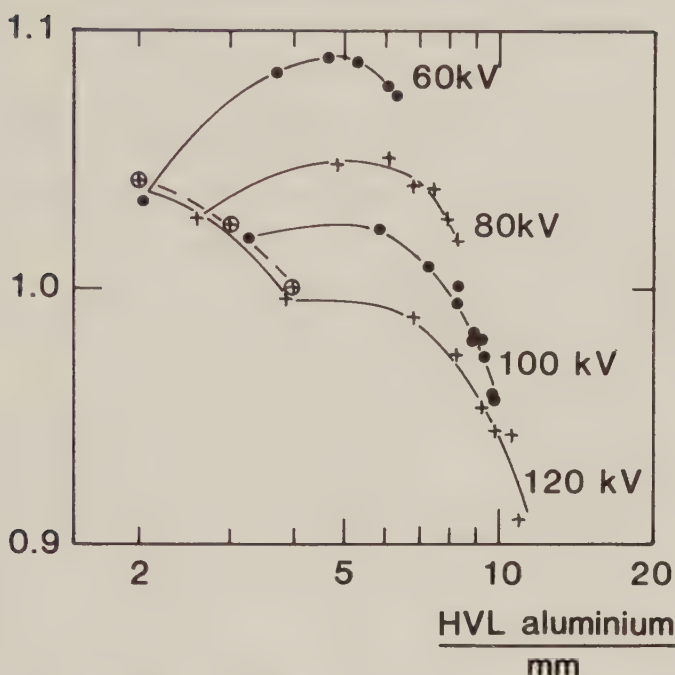


Figure 1. X-ray exposure calibration factor versus exposure half-value-layer in aluminium of radiation distributions produced at various x-ray tube potentials.  $\oplus$  -----  $\oplus$  : relative calibration curve published by the manufacturer of the ionization chamber.

The responses at 60, 80, 100 and 120 kV with no extra filter correspond to the calibration curve published by the manufacturer. In view of the ionization chamber's high sensitivity to variations in radiation distribution, the agreement, in relative terms, between these two curves is remarkably good. A comparison in absolute terms is not relevant, since the manufacturer reports the "quality response of a typical chamber".

To verify the somewhat unusual calibration results obtained from the E.I.L. ionization chamber, its response was also compared to that of an ionization chamber, PTW,  $30 \text{ cm}^3$ , which had been calibrated at a regional calibration laboratory in the USA. Since the data, thus obtained, agreed within about  $\pm 2 \%$  with the former results, the calibration curves, presented in Figure 1, were considered to be confirmed.

Although the radiation quality response of the E.I.L. ionization chamber, established by the above investigation, has to be accepted as being as good as can be achieved at present, further studies are relevant, since several interesting questions arose in conjunction with this calibration.

### 2.3 Exposure rate - Reciprocity law failure of the film.

When the sensitivity of a screen-film system is measured, not only the radiation quality but also the x-ray exposure-rate to which the systems are subjected, have influence on the results. An example of this is demonstrated in Figure 2. Here the x-ray exposure, needed to produce the

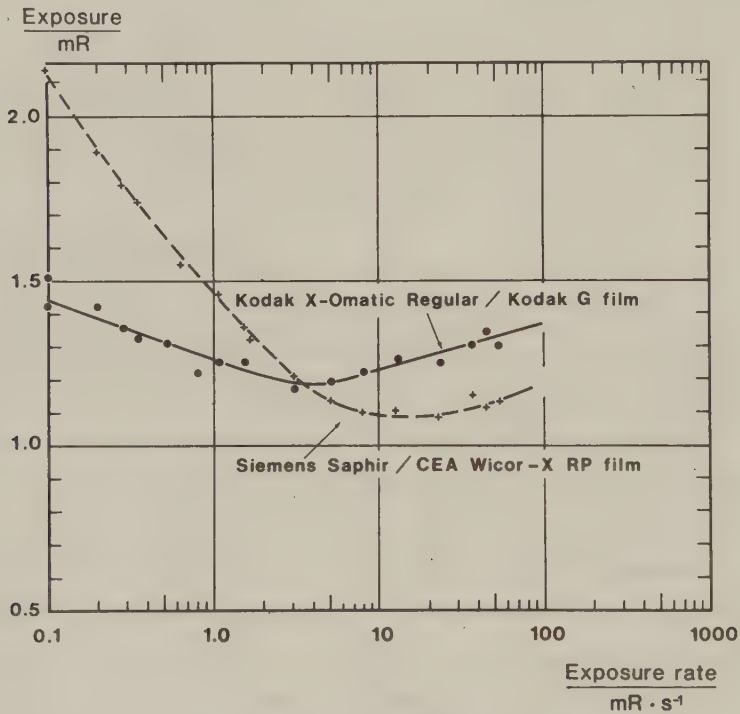


Figure 2. Reciprocity law failure. X-ray exposure needed for production of equal film density versus x-ray exposure rate. (Holje and Svahn, 1974).

net density 1.0 of the films, i.e. the reciprocal sensitivity, is plotted versus the x-ray exposure-rate for two screen-film systems. Figure 2 shows that, in the case of the Saphir/Wicor-X RP system, almost twice the minimum x-ray exposure is needed, when the system is exposed to very low

exposure-rates, corresponding to tomography exposures. Figure 2 also shows, that the sensitivity ratio between the two systems changes with exposure-rate. At exposure-rates below circa 3 mR/s, the X-Omatic system has the highest sensitivity, but at exposure-rates above this value, the Saphir system has the highest sensitivity. This effect of exposure-rate on the screen-film sensitivities is due to the non-proportionality between film density and exposure when the films are exposed to very low and very high light intensities. This is called the reciprocity law failure (Hamilton, 1966).

Arnold et al. (1978) have made an investigation of the reciprocity law failure of some of the new green sensitive films compared with that of one of the conventional blue sensitive films. Their results show that the green sensitive films exhibit larger failure than the specific blue sensitive film incorporated in their study.

An investigation of screen-film sensitivities and their variations with radiation quality incorporates several steps where errors can be introduced due to a reciprocity law failure of the films. These can be avoided by exposing the films to constant light intensity throughout the measurements. - The different film densities in an H&D-curve should thus be produced at the same light intensity. This requirement is fulfilled when the exposures are made at constant x-ray exposure rate using a time-scale sensitometer. - In evaluations of the influence of radiation quality on the screen-film sensitivity, the use of constant x-ray exposure time will yield constant light intensity. - In evaluations of the relative sensitivity of several screen-film systems, errors due to a reciprocity law failure are somewhat more difficult to eliminate. The spectral distribution of the light emitted by the different screens may differ, and the film may have different sensitivity to these distributions. Equal light exposures may, therefore, not yield equal film densities, although constant light intensity is employed. When such systems are exposed to the same film density at equal exposure time, higher light intensities and light exposures are employed in systems, which emit light in regions where the film's sensitivity is low. If the film itself, however, is employed as the light detector, these two

quantities will be considered as independent of the light distribution emitted by the screens. Since this agrees with the actual circumstances, there are good reasons to believe that errors due to reciprocity law failure are avoided when these sensitivity measurements are performed at constant exposure times.

X-ray exposures in the majority of radiographic examinations, however, are made at maximum permissible tube loading and the exposure-time is adjusted to obtain correct exposures. Failures of the reciprocity law are, therefore, incorporated in the sensitivity differences encountered under clinically relevant exposure conditions. The use of constant tube loading, when several screen-film systems are exposed to a certain radiation quality, further means that the x-ray exposure rate is constant. To simulate more realistic exposure conditions, the screen-film sensitivities at the various radiation qualities were therefore evaluated at constant x-ray exposure rate, namely 15 mR/s. This exposure rate is well within the range of exposure rates occurring at various diagnostic examinations (Holje et al., 1973, unpublished data).

Two additional series of exposures of the various screen-film systems were made in conjunction with noise evaluations (Holje and Doi, 1982) and image quality studies (Holje, 1977, unpublished data). These latter exposures were made at the radiation quality 80 kV and 20 mm aluminium and with 0.1 s exposure time. The relative screen-film sensitivities, evaluated at constant exposure time, were found to be directly proportional, within the experimental errors, to the sensitivities evaluated at constant x-ray exposure rate. This indicates that the reciprocity law failures of the two films do not have any significant influence on the screen-film sensitivity under the exposure conditions used in this study.

### 3. RESULTS AND DISCUSSION.

#### 3.1 Screen-film sensitivities at the radiation quality produced at 80 kV and 20 mm aluminium filter.

Table 2, Column 1, presents the experimentally determined x-ray exposures, needed to produce a net density of 1.0 of the films in the various screen-



TABLE 2.

| Intensifying<br>screen | Exposure<br>$R \times 10^{-3}$ | Sensitivity<br>$(\text{keV}/\text{cm}^2)^{-1}$ | Abs. Energy<br>$\text{keV}/\text{cm}^2$ | Light Yield<br>$(\text{keV}/\text{cm}^2)^{-1}$ |
|------------------------|--------------------------------|------------------------------------------------|-----------------------------------------|------------------------------------------------|
| M.R. 50                | 1.2                            | $5.78 \times 10^{-10}$                         | $4.42 \times 10^8$                      | $2.26 \times 10^{-9}$                          |
| M.R. 200               | 0.44                           | $1.51 \times 10^{-9}$                          | 2.05 "                                  | 4.87 "                                         |
| M.R. 400               | 0.21                           | 3.10 "                                         | $9.04 \times 10^7$                      | 11.06 "                                        |
| M.R. 600               | 0.14                           | 4.85 "                                         | 8.91 "                                  | 11.23 "                                        |
| SE 2                   | 0.43                           | 1.56 "                                         | see M.R. 200                            |                                                |
| SE 4                   | 0.22                           | 2.99 "                                         | see M.R. 400                            |                                                |
| SE 6                   | 0.14                           | 4.88 "                                         | see M.R. 600                            |                                                |
| Blue Max 1             | 0.44                           | 1.51 "                                         | see M.R. 200                            |                                                |
| Blue Max 2             | 0.20                           | 3.29 "                                         | see M.R. 400                            |                                                |
| Rare Earth             | 0.17                           | 3.84 "                                         | $9.91 \times 10^7$                      | $10.09 \times 10^{-9}$                         |
| Titan 923              | 0.17                           | 3.86 "                                         | 7.48 "                                  | $13.88 \times "$                               |
| Cronex Quanta II       | 0.20                           | $3.41 \times 10^{-9}$                          | $9.13 \times 10^7$                      | $10.95 \times 10^{-9}$                         |
| Type 4360              | 0.32                           | 2.10 "                                         | $1.23 \times 10^8$                      | 8.16 "                                         |
| Type 6359              | 0.23                           | 2.89 "                                         | 1.17 "                                  | 8.59 "                                         |
| X-Omatic Reg.          | 0.46                           | 1.45 "                                         | 2.39 "                                  | 4.19 "                                         |
| Cronex Par Sp.         | 1.0                            | $6.45 \times 10^{-10}$                         | $2.40 \times 10^8$                      | $4.17 \times 10^{-9}$                          |
| Rubin Super            | 4.6                            | 1.44 "                                         | $1.29 \times 10^9$                      | $7.77 \times 10^{-10}$                         |
| Grenex G-4             | 0.38                           | $1.75 \times 10^{-9}$                          | $1.75 \times 10^8$                      | $5.71 \times 10^{-9}$                          |
| Grenex G-8             | 0.17                           | 3.91 "                                         | $9.99 \times 10^7$                      | 10.02 "                                        |
| Lanex Fine             | 0.56                           | 1.18 "                                         | $2.26 \times 10^8$                      | 4.43 "                                         |
| Lanex Regular          | 0.15                           | 4.55 "                                         | 1.03 "                                  | 9.73 "                                         |
| Trimax Alpha 4         | 0.37                           | 1.80 "                                         | 1.33 "                                  | 7.51 "                                         |
| Trimax Alpha 8         | 0.18                           | 3.75 "                                         | 1.04 "                                  | 9.59 "                                         |
| Rarex BG Detail        | 0.50                           | $1.34 \times 10^{-9}$                          | $2.10 \times 10^8$                      | $4.76 \times 10^{-9}$                          |
| Rarex BG Mid Sp.       | 0.26                           | 2.56 "                                         | 1.61 "                                  | 6.23 "                                         |
| Rarex BG High Sp.      | 0.15                           | 4.43 "                                         | 1.12 "                                  | 8.92 "                                         |
| Rarex B Mid Speed      | 0.19                           | $3.48 \times 10^{-9}$                          | $7.90 \times 10^7$                      | $12.66 \times 10^{-9}$                         |

film systems. By use of a conversion factor (Holje, 1983 f) these exposure values were converted into the corresponding energy fluences. In Column 2 of Table 2, the sensitivities are determined as the reciprocal of the energy-fluences needed to produce a net density of 1.0 of the films.

$$S_{80,20}(X) \cdot \frac{1}{(\Psi/X)_{80,20}} = S_{80,20}(\Psi) = 1 / \int_{h\nu \text{ min}}^{80} \left( \frac{d\Psi}{dh\nu} \right)_{80,20} dh\nu \quad (1)$$

$S_{80,20}(X)$  is the reciprocal exposure needed to produce the net film density of 1,0 at 80 kV filtered with 20 mm aluminium, i.e. the sensitivity expressed in reciprocal exposure unit

$(\Psi/X)_{80,20}$  is the exposure-to-energy fluence conversion coefficient at 80 kV filtered with 20 mm aluminium

$S_{80,20}(\Psi)$  is the sensitivity at 80 kV filtered with 20 mm aluminium expressed in reciprocal energy fluence unit

$\int_{h\nu \text{ min}}^{80} \left( \frac{d\Psi}{dh\nu} \right)_{80,20} dh\nu$  is the energy fluence needed to produce net film density of 1,0 at 80 kV filtered with 20 mm aluminium.

According to Table 2, the sensitivity of the new screen-film systems may be as high as 7.5 times that of the Par Speed  $\text{CaWO}_4$ -system. This sensitivity gain has been achieved by increased energy absorption, and also by increased light-yield of the new screens. It has been shown that the energy absorption of the new intensifying screens is at most a factor of 3 higher than that of the Par Speed  $\text{CaWO}_4$ -screens (Holje, 1983 b). The remaining fraction of the sensitivity gain, i.e. a factor of 2.5 must be due to the higher light-yield of the new x-ray phosphors (Section 3.5).

### 3.2 The energy deposited per unit screen area to produce the film density 1.0.

The energy absorbed per unit area, discussed in this section, is an important factor in studies of radiographic image quality of screen-film systems. This quantity is used in the following to derive a measure of the

light-yield of the intensifying screens. It also provides basic information for the calculations of noise equivalent number absorption events in the screen-film systems; a concept discussed in another paper (Holje, 1983 d).

The product of the incident energy fluence needed to produce a net film density of 1.0 and the energy absorption by the screens yields the energy deposited per unit screen area. Since x-ray distributions are used, the product of the differential energy fluence and the energy absorption of photons with energy,  $h\nu$ , was determined in increments of 1 keV and integrated over the energy range of interest,  $h\nu_{\min}$  to  $h\nu_{\max}$ :

$$C_{x,y} = \int_{h\nu_{\min}}^{h\nu_{\max}} B(h\nu) \cdot \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu \quad (2)$$

$C_{x,y}$  is the energy deposited per unit screen area at x kV filtered with y mm aluminium

$B(h\nu)$  is the energy absorption of photons with energy  $h\nu$  (Holje, 1983 b)

$h\nu_{\max}$

$\int_{h\nu_{\min}}^{h\nu_{\max}} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu$  is the energy fluence needed to produce net film density 1,0 at x kV filtered with y mm aluminium.

The radiation quality dependence. These calculations were performed for each screen-film system when exposed to twenty different radiation qualities (Holje, 1983 f). The mean value of the energy deposited at the various radiation qualities was then calculated for each screen-film system. It was found that the energies deposited per unit screen area, when they were exposed to the various discrete radiation qualities, were randomly distributed around these calculated mean values. 95 % of all data were within  $\pm 10$  % of their mean values and all data within  $\pm 15$  %.

Figure 3 illustrates these findings. The data have been normalized to those achieved with the radiation distribution produced at 80 kV filtered with 20 mm aluminium. Due to the large

Relative energy absorbed

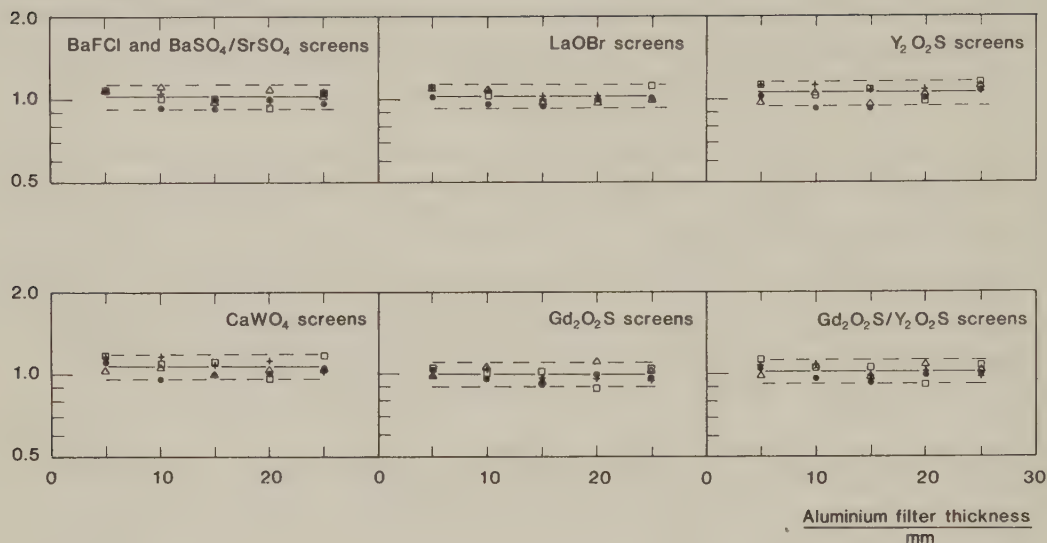


Figure 3. Energy absorbed in intensifying screens of different chemical composition at various incident radiation qualities relative to that at 80 kV filtered with 20 mm aluminium.  $\Delta$ — 60 kV,  $\bullet$ — 80 kV,  $\square$ — 100 kV and + — 120 kV x-ray tube potential.

number of intensifying screens incorporated in the study, those intensifying screens with the same high atomic number element(s) are presented as one group. The data points in Figure 3 are the mean values, at each radiation quality, of data for all of the screens belonging to the specific group. The mean value of all data in a group is indicated as a solid line and an interval of  $\pm 10\%$  around this value is marked.

The random fluctuations of data on the energy absorbed in the screen-pairs are predominantly related to errors in the sensitivity measurements, where several sources of uncertainties are involved. Errors due to uncertainties in the radiation quality dependence of the ionization chamber and in its calibration may amount to  $\pm 5\%$ . To these are added uncertainties in the sensitivity determinations, which are caused by screen inhomogeneities and variations in film sensitivity. These are estimated to be about  $\pm 3\%$ . Fluctuations in the developer conditions may give rise to sensitivity variations of about  $\pm 5\%$ . This results in an overall uncertainty of about  $\pm 8\%$  in the sensitivity measurements. Compared to this, the maximum

registered deviation of  $\pm 10\%$  for 95 % of the data on energy absorbed seems reasonable.

Vyborny (1976) has reported an increase of the energy absorbed by intensifying screens for production of a certain film density at incident photon energies below 20 - 30 keV. This increase was explained by the high absorption of these photons at their very entrance into the screens, whereby the light produced has an increased probability to be absorbed before reaching the film. The conclusion, which can be drawn from the results obtained here, is that the energy deposited per unit screen area to give a certain film density is independent of the radiation qualities, 60 - 120 kV filtered with 5 - 25 mm aluminium. It should be noted, that no photons with energies below 20 - 30 keV exist in these radiation distributions.

The energy deposited per unit area of the screen-film systems. Table 2, Column 3, presents the energy deposited per unit screen-area to produce a net density of 1.0 for the films of all the screen-film systems investigated. In previous investigations (Holje et al., 1977; Holje and Doi, 1982) it has been concluded that the M.R. screens, Blue Max screens and SE screens were essentially the same screens marketed under different names. This conclusion was based on the fact that the attenuation, sensitivity and resolution properties of the M.R. 200, Blue Max 1 and SE 2 screens were the same. Similar results were obtained for M.R. 400, Blue Max 2 and SE 4, as well as for M.R. 600 and SE 6 screens. For this reason, and since these screens will be modified in the near future, determinations of the energy deposited were made on the M.R. screens only. For practical purposes, the M.R. 200 data are considered applicable for the Blue Max 1 and SE 2 screens, the M.R. 400 data to be valid for the Blue Max 2 and SE 4 screens, and the M.R. 600 data to be valid for the SE 6 screens, as indicated in Table 2.

Data in Table 2 on the energy deposited in the various screen pairs are determined at 80 kV filtered with 20 mm aluminium. According to the conclusions above, however, these data can be used as representative for all of the radiation qualities studied. The table shows that all new intensifying screens, except the M.R. 50 screens, need less absorbed energy than



the Par Speed  $\text{CaWO}_4$ -system in order to yield the same film-density. The data in Table 2 also indicate that as little as  $1/3$  of the energy deposited in the Par Speed  $\text{CaWO}_4$ -screens is required in some of the new high sensitivity systems, such as Titan 923 and Rarex B Mid Speed. It will be shown that there is an inverse relationship between these data and the appearance of quantum mottle in the images (Holje, 1983 d). From the ratios between the energies deposited, one can make a crude estimation at this stage that the noise levels in these new high sensitive systems are about three times higher than that in the Cronex Par Speed system.

### 3.3 Screen-film sensitivities; their dependence on radiation quality.

In Figures 3, it was shown that the energy deposited per unit screen area for production of a certain film density was independent of the radiation qualities used. An important consequence of this finding is that this allows the relative sensitivities of the screen-film systems to be theoretically determined from their energy absorption properties.

Relative sensitivities expressed as relative reciprocal energy-fluences. In Equation 1, the screen-film sensitivity was expressed as the reciprocal of the energy fluence needed to produce a net density of 1.0 for the films. The sensitivity at the radiation quality produced at  $x$  kV filtered with  $y$  mm aluminium, relative to that at 80 kV filtered with 20 mm aluminium,  $S_{\text{Rel.},x,y}$  may be expressed as:

$$S_{\text{Rel.},x,y}(\Psi) = \frac{S_{x,y}(\Psi)}{S_{80,20}(\Psi)} = \frac{\int_{h\nu \min}^{h\nu \max} \left(\frac{d\Psi}{dh\nu}\right)_{80,20} dh\nu}{\int_{h\nu \min}^{h\nu \max} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu} \quad (3)$$

Since the absorbed energy per unit screen area,  $C_{x,y}$ , in Equation 2 has

been shown to be constant, we have:

$$\frac{C_{x,y}}{C_{80,20}} = \frac{\int_{h\nu \min}^{h\nu \max} B(h\nu) \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu \min}^{h\nu \max} B(h\nu) \left(\frac{d\Psi}{dh\nu}\right)_{80,20} dh\nu} = \quad (4)$$

$$= \frac{B_{x,y} \cdot \int_{h\nu \min}^{h\nu \max} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{B_{80,20} \cdot \int_{h\nu \min}^{h\nu \max} \left(\frac{d\Psi}{dh\nu}\right)_{80,20} dh\nu} = 1$$

$B(h\nu)$  is the energy absorption of photons with energy  $h\nu$  and

$B_{x,y}$  is the energy absorption weighted according to the energy fluence distribution produced at  $x$  kV filtered with  $y$  mm aluminium (Holje, 1983 b).

By combining Equations 2, 3 and 4 we have:

$$S_{\text{Rel},x,y}(\Psi) = \frac{S_{x,y}(\Psi)}{S_{80,20}(\Psi)} = \frac{B_{x,y}}{B_{80,20}} \quad (5)$$

The sensitivity of a screen-film system at an arbitrary radiation quality, relative to that at 80 kV and 20 mm aluminium filter, is thus simply equal to the relative energy absorption of the intensifying screens.

The relationship between relative sensitivity and relative energy absorption. Figure 4 shows the sensitivities of the screen-film systems at the various radiation qualities, relative to that at 80 kV filtered with 20 mm aluminium. All of the screen-film systems with the same high atomic number element(s) in their phosphor layers are treated together.

Relative sensitivity,  $S_{\text{Rel.}}(\psi)$

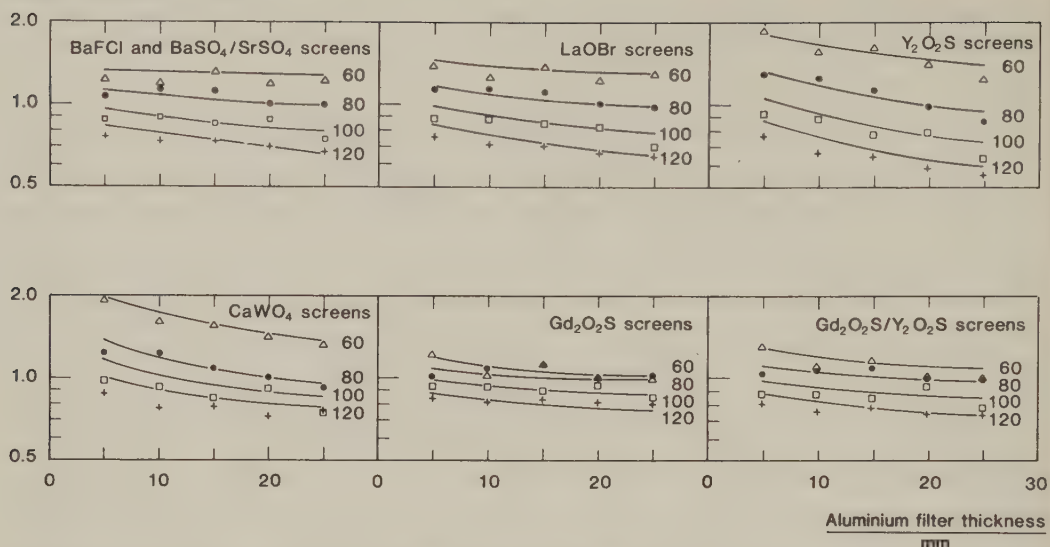


Figure 4. Sensitivity of screen-film systems at various radiation qualities relative to that at 80 kV filtered with 20 mm aluminium.  $\Delta$ —60 kV,  $\bullet$ —80 kV,  $\square$ —100 kV and  $+$ —120 kV. The curves indicate the energy absorption by the screens at various radiation qualities relative to that at 80 kV filtered with 20 mm aluminium. (Holje, 1983 b).

The data points in Figure 4 are the average of the experimentally determined relative sensitivities of all of the screen-film systems belonging to each group. The average values were chosen for this presentation, since the accuracy of the experimentally determined sensitivities was not high enough to make any definite distinctions between systems made of the same screen phosphors. The curves in Figures 4 indicate the corresponding calculated relative sensitivities. These were calculated from energy-absorption data according to Equation 5.

The agreement between measured and calculated sensitivities is rather striking if one considers that these two values have been independently derived through several complicated measurements and calculations. Among these are the assessments of the radiation quality response of the ionization chamber, the x-ray spectral distributions, the exposure to energy fluence conversion factors, the attenuation properties of the intensifying screens, the reabsorption of inherently produced K x-rays, the mass attenuation coefficients of the phosphors and the energy absorption in the

screens.

Figure 4 confirms the relationship expressed in Equation 5 and establish that the relative sensitivity characteristics of the screen-film systems are determined exclusively by the energy absorption properties of the intensifying screens. It was not possible, however, to detect the subtle difference in energy-responses of thin and thick screens. This was due to the limited accuracy of the sensitivity measurements. These differences, however, were investigated in a study of the energy absorption properties of the intensifying screens (Holje, 1983 b).

In conjunction with the investigation of the energy absorption properties of the intensifying screens, the resulting image contrast was also discussed. Its dependence upon screen thickness, phosphor materials and choices of x-ray tube potential was treated. Since the results here show that the sensitivity characteristics are reflections of the energy absorption properties of the intensifying screens, further discussion of the energy dependence and its influence on the final image contrast is not necessary, and the reader is referred to the discussion held in connection with the energy absorption properties (Holje, 1983 b).

Adjustments of x-ray exposure to obtain correct film density. Adjustments of the x-ray exposure have to be made to obtain correct film density. In practical clinical work, these adjustments are made by changes in exposure time, tube current and/or tube potential. X-ray exposure tables, a so called point system, have been developed (Schwarz, 1961) for calcium tungstate systems and x-ray generators are available where adjustments in exposure time, tube current and tube potential are made in steps of one point, based on this system. Due to differences in energy response, however, adjustments in tube potential may not give the same change in the film's density when it is combined with screens made of new phosphor materials. An example of this is illustrated by the sensitivity of  $\text{Gd}_2\text{O}_2\text{S}$ -systems, compared to that of  $\text{CaWO}_4$ -systems, at x-ray tube potentials between 60 kV and 80 kV. This is shown in Figure 4. Over the complete range of aluminium filter thicknesses, the sensitivity of calcium tungstate systems at 60 kV is about 50 % higher than that at 80 kV, whereas the corresponding sensitivities in  $\text{Gd}_2\text{O}_2\text{S}$ -screens differ by less than 10 %.

Changes in x-ray tube potential to achieve correct exposure of conventional  $\text{CaWO}_4$ -systems, therefore, are counteracted by their energy response, namely, increased x-ray tube potential increases the x-ray exposure, but the system's sensitivity decreases. The energy response of  $\text{Gd}_2\text{O}_2\text{S}$ -systems, on the other hand, remains almost constant, which makes these systems more sensitive to the corresponding changes in tube potential.

Since  $\text{CaWO}_4$  was the commonly used phosphor material in the past, the point-system was worked out for systems based on this phosphor, and there was no obvious reason for any separate analysis of x-ray tube out-puts and energy responses of the systems. When the new screen-film systems were introduced, however, problems arose, since most users were not aware of their different energy responses and their effect on the film density. Complaints came, saying that the new systems were too sensitive to exposure changes, and that films came out either over- or underexposed. (In extreme cases, it was concluded that the new systems could not be used in diagnostic radiology!). The example above explains why these problems arose.

Unfortunately, sufficient information about the characteristics of the new systems was not available at the time when they were introduced. Many mistakes, which gave rise to unnecessary patient exposure, would have been avoided if data, like those presented in Figure 4, had been available. It is now quite obvious that the differences in sensitivity characteristics of screen-film systems of different chemical compositions must be taken into account when the x-ray exposures are made. When small adjustments of the x-ray exposure have to be made to obtain correct film density, these should be made by adjustments of the x-ray tube current and/or the exposure time. Adjustments of the x-ray tube potential should be avoided, since they may not give the expected change in film density, which in turn results in re-takes and unnecessary exposure of the patient.

#### Relative sensitivities expressed as relative reciprocal x-ray exposures.

The sensitivity is often expressed in the literature as the reciprocal of - or just as the x-ray exposure needed to produce a certain film density (Sprawls, 1977; Holje et al., 1977; Johns and Cunningham, 1969; Rao



et al., 1978). The relationship between the sensitivity, expressed as reciprocal energy fluence, and that expressed as reciprocal x-ray exposure, is given in Equation 1. By inserting Equation 1 in Equation 5, the expression for the relative sensitivity becomes:

$$S_{\text{Rel.,x,y}}(\chi) = S_{\text{Rel.,x,y}}(\psi) \cdot \frac{(\psi/\chi)_{x,y}}{(\psi/\chi)_{80,20}} = \frac{B_{x,y}}{B_{80,20}} \cdot \frac{(\psi/\chi)_{x,y}}{(\psi/\chi)_{80,20}} \quad (6)$$

Equations 5 and 6 clearly indicate that two quite different expressions are obtained if the relative sensitivity is expressed as relative reciprocal energy-fluence or as relative reciprocal exposure. The relative sensitivities of the screen-film systems, expressed according to Equation 6, are shown in Figure 5.

The risk for misinterpretation of the radiation quality dependence of the sensitivity, when expressed in terms of relative reciprocal exposure. The data points in Figure 5 indicate the relative sensitivities of the systems, experimentally determined by means of exposure measurements. The curves indicate corresponding calculated data, determined according to Equation 6 from energy absorption data and exposure to energy fluence conversion factors (Holje, 1983 b, f).

Figure 5 is shown solely for the purpose of illustrating how the physical quantities affect the "energy dependence" of the screen-film systems. For example, when looking at Figure 5, one can assume that the sensitivity of  $\text{CaWO}_4$ -systems is independent of radiation quality, while the truth is, as shown in Figure 4, that the sensitivity of these systems is heavily energy dependent. The apparent energy independence, shown in Figure 5, is a result of expressing the sensitivity in terms of reciprocal exposure. The introduction of this physical quantity means that screen-film sensitivity is not described simply by the energy fluence needed to produce a net density of 1.0 for the films, but also by its capacity to ionize air. This extension of a straight forward quantification of screen-film sensitivity to also include physical properties of air makes the expression for a genuine screen-film property very complicated. This is demonstrated

Relative sensitivity,  $S_{Rel} (X)$

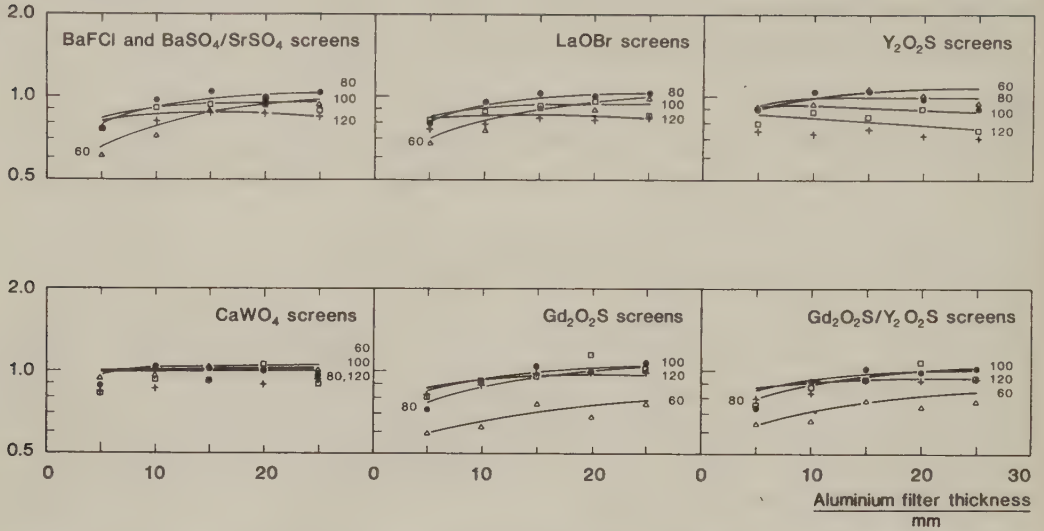


Figure 5. Sensitivity of screen-film systems, expressed as reciprocal exposure, at various radiation qualities relative to that at 80 kV filtered with 20 mm aluminium.  $\Delta$  — 60 kV,  $\bullet$  — 80 kV,  $\square$  — 100 kV and  $+$  — 120 kV. The curves indicate the corresponding relative sensitivity determined from the energy absorption in the intensifying screens.

by the following analysis of the expression in Equation 6.

The exposure-to-energy fluence conversion factors can be expressed as a constant divided by appropriate mass energy absorption coefficients of air (Holje, 1983 f). By employing this in Equation 6, the following expression for relative sensitivity is obtained:

$$S_{Rel.,x,y} (X) = \frac{B_{x,y}}{B_{80,20}} \cdot \frac{((\mu_{en}/\rho)_{air})_{80,20}}{((\mu_{en}/\rho)_{air})_{x,y}} \quad (7)$$

$(\mu_{en}/\rho)_{x,y}$  is the mass energy absorption coefficient of air weighted according to the energy fluence distribution produced at x kV filtered with y mm aluminium.

This relation clearly illustrates how the sensitivity characteristics, when expressed in terms of relative reciprocal exposures, are influenced by the absorption properties of the screens, as well as by the absorption properties of air.

The mass energy absorption coefficients of air weighted according to the various radiation qualities, relative to that at 80 kV filtered with 20 mm aluminium  $((\mu_{\text{en}}/\rho)_{\text{air}})_{x,y} / ((\mu_{\text{en}}/\rho)_{\text{air}})_{80,20}$ , have been determined (Holje, 1983 f). The most striking agreement exists between these energy absorption characteristics of air and those of the  $\text{CaWO}_4$ -systems presented in Figure 4. When combining these two energy absorption characteristics according to Equation 7, the outcome must therefore be that the sensitivity of  $\text{CaWO}_4$ -systems, expressed in terms of relative exposure units, adopts a constant value at all of the radiation qualities studied.

From the above example it is obvious that the characterization of screen-film sensitivity in terms of reciprocal exposure is confusing, and may be misleading when interpreting "the energy dependence". The use of reciprocal exposure, as a measure of sensitivity, also makes its direct relation to the energy absorption in the screens difficult to ascertain.

### 3.4 Relative light-yield of screen-film systems.

Intrinsic efficiency and light-yield. One of the great advantages with the new phosphor materials is that their intrinsic efficiency, defined as the total light energy produced per unit x-ray or electron energy absorbed by the phosphor, is substantially higher than that of conventional  $\text{CaWO}_4$ -phosphor (Buchanan et al., 1972; Stevels and Pingault 1975). To obtain their fluorescent properties, all new phosphors however, have to be activated with a tracer. The exact amount of this element is critical for the resultant efficiency. Similar qualities of phosphor, produced by different manufacturers, may, therefore, differ in their intrinsic efficiency.

The completed intensifying screens are composed of a layer of the phosphor material, which is mixed with a binding substance and coated on a support of plastic or cardboard. The technology of this screen coating process can heavily affect the fraction of the light produced by the phosphor which will reach the film. For example, a common way to improve screen-film sensitivity is to enhance the light emittance from the surface of the screen. This can be done simply by applying the fluorescent layer on a light reflecting cardboard or plastic support, or by adding a reflective layer between the phosphor layer and its support. - When high resolution

of a system is desired, light scattering in the phosphor layer should be reduced. An absorbing layer is often used, as well as a light absorbing dye, which is mixed into the fluorescent layer. -

The intensity of the produced light is thus reduced by various degrees before reaching the film. The light energy emitted from the screen surface per unit x-ray energy absorbed, therefore, becomes a property which is specific for each individual intensifying screen. Data on the intrinsic efficiency of the phosphor in the screen is a measure of the maximal light energy which can possibly be emitted from the completed screen. It gives information about the potential of the screen and is, therefore, of great importance, especially for the design of the screens.

Since this study is focussed upon characteristics of commercially available screen-film systems, the properties of the entire screens rather than of the constituent phosphor are of immediate interest. An attempt has been made to provide a quantitative measure of the light energy emitted from the surface of the screen per unit x-ray energy absorbed. This measure refers only to the light energy emitted from the screen surface, which is directed towards the film and is here called "light-yield". Indicators of the light-yield of the screen-film systems, LY, have been determined, using the energy deposited per unit screen-area as input signal and a certain film density as output signal:

$$LY = \frac{\text{film density}}{\text{energy deposited per unit screen area}} \quad (8)$$

Since all films were exposed to a net density of 1.0, the relative light-yield was obtained simply as the reciprocal of the energy deposited per unit screen-area from Equation 2.

$$LY = \frac{\text{net density 1.0}}{C_{x,y}} \sim (C_{x,y})^{-1} \quad (9)$$

Since the spectral light sensitivity of the x-ray film is not constant over the wave length interval of interest, this determination of light-yield has certain limitations in that it does not give a true measure of the light energy emitted from the surfaces of the screens. This variation



in spectral sensitivity is especially limiting when many different light-emission spectra are involved, ranging from ultra-violet to the green region of light. A change of the spectral sensitivity of the x-ray film will result in changes of the relative light-yield of systems emitting different light distributions. It appears, however, that the spectral light sensitivity of conventional x-ray films from different manufacturers do not differ significantly. A change of film type would, therefore, not cause any noticeable change of the relative light-yield among such systems (Holje and Persson, 1980).

The conventional x-ray film is sensitive mainly to ultra-violet and blue light, and, therefore, a green-sensitive type of film has been employed for the green-emitting screens. This need of two film types has the disadvantage that a change in relative sensitivity of one of the two films will result in a shifting of the relative light-yield between the "blue" and "green" groups of screen-film systems.

Since most of the "green"-emitting screens are made of gadolinium oxysulphide, their light distributions are expected to be very similar. This implies that the relative light-yields among these systems may remain unaffected, even if there is a change in the spectral sensitivity of the green-sensitive film.

Despite these disadvantages, the use of x-ray film as a light detector is advantageous in the sense that it gives relative light-yield values which are valid in practical clinical situations.

The relative light-yields of the screen-film systems investigated are presented in Table 2, Column 4. The data are determined at 80 kV filtered with 20 mm aluminium, but, since the energy deposited per unit screen area to produce a certain film density has been shown to be independent of radiation quality, these data are valid also for the other radiation qualities studied.

The data in Table 2 show that only one of the new screen-film systems, namely M.R. 50, has lower light-yield than the Par Speed  $\text{CaWO}_4$ -system. The table also shows that the light-yield of one of the new high sensitivity systems (Titan 923) is more than three times higher than that of the Par Speed  $\text{CaWO}_4$ -system.



It is interesting to note that the two systems (M.R. 50 and Titan 923), representing the lowest and highest light-yields observed with the new systems, are both made of LaOBr:Tb. Although the intrinsic efficiencies of these phosphors presumably are comparable, the relative light-yields of these screens differ by a factor of six. This difference can be assumed to be due predominantly to the screen technology, which is different in these two cases. The M.R. 50 screens contain a heavy dye, which reduces light diffusion, thus enhancing the resolution of the system. The Titan 923 screens, on the other hand, have light reflecting layers, which improve their light emission towards the film and, thus, their sensitivity.

The thicknesses in three sets of the screen pairs, namely M.R. 50 and M.R. 600, Lanex Fine and Lanex Regular, and Rarex BG Detail and Rarex BG High Speed, differ by a factor of two (Holje, 1983 a). It has been shown (Holje, 1983 b) that the energy absorptions in the three thicker screen-pairs in question are between 1.7 and 1.8 times greater than those in the corresponding thin (one-half thickness) screen-pairs.

Data in Table 2 show that an increase in sensitivity by a factor of 8.5 is achieved when changing from M.R. 50 to M.R. 600 screens. This increase is five times higher than the increase in energy absorption alone. These results give pronounced illustration of the importance of the light-yield of the screens, and its influence on screen-film sensitivity. In this case, the light-yield of the thick screen pair is a factor of five higher than that of the thin screen pair. The large difference in the light-yields of these two screen pairs is due to the light absorbing dye, which has been added to reduce the light diffusion in the M.R. 50 screens.

The difference in sensitivities between the other two sets of screen pairs Lanex Regular and Fine, and Rarex BG High Speed and Detail, is 3.3 and 3.8 respectively, which is much smaller than that in the above example. The increases in sensitivity are here only about a factor of two higher than the increases of energy absorptions alone. In these two cases, the light-yields of the thick screen pairs are about twice as high as those of the thin screen pairs, 2.2 and 1.9 respectively. It is very interesting to observe here that the sensitivity gains obtained, when changing from these two low sensitive screen pairs to those of high sensitivity, are

accomplished by almost equal increases in the energy absorption and light-yield.

### 3.5 Sensitivity, the balance between energy absorption and light-yield.

Sensitivity, energy absorption and light-yield of the screen-film systems. The energy absorption and the light-yield are important screen characteristics which, together with the sensitivity of the film, determine the final sensitivity of the screen-film system. Figure 6 presents a comprehensive demonstration of the relationship between the relative light-yield, energy absorption and sensitivity of all of the screen-film systems investigated. The data are evaluated at the radiation distribution produced with 80 kV filtered with 20 mm aluminium. The identity of each screen-film system is not indicated in the figure, but all of the systems can, however, easily be identified by use of the data in Table 2.

The three diagonal lines in Figure 6 indicate 12.5 %, 25 % and 50 % energy absorption. This parameter is of special interest, since it represents a physical property of the phosphors alone, whereas the relative light-yield, as well as the sensitivity, also include the sensitivities of the films. If the screens, therefore, are combined with films of other sensitivities, the relative light-yield and the sensitivity will change, while the energy absorption, of course, remains the same. This results in a shifting of the data points that is parallel to the dotted diagonal lines.

Figure 6 shows that the screen-film system with the highest sensitivity, the lanthanum oxybromide system, M.R. 600, has more than seven times higher sensitivity than the Par Speed calcium tungstate system. It is evident from this illustration, that this increase in sensitivity has been attained partly by increased energy absorption and partly by increased relative light-yield. In addition, it should be noted that the magnitude of these increases of energy absorption and light-yield is equal.

A solid line connects the Par Speed calcium tungstate system and this high sensitive lanthanum oxybromide system. Below this, a parallel solid line is shown, originating at the gadolinium oxysulphide system, Lanex

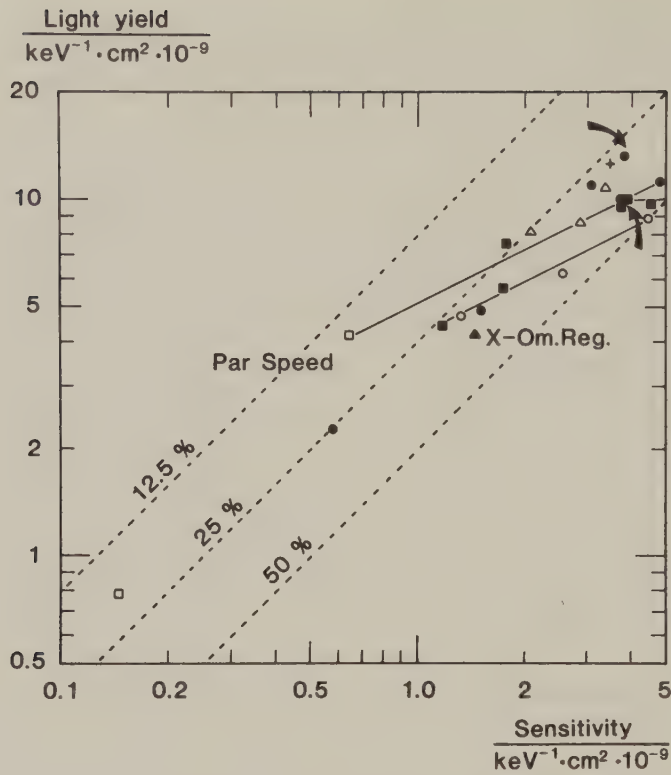


Figure 6. Sensitivity, light-yield and energy absorption of the screen-film systems at 80 kV filtered with 20 mm aluminium. The energy absorptions 12,5 %, 25 % and 50 % are indicated by the dotted lines.

+ —  $\text{Y}_2\text{O}_2\text{S}$ -screens,  $\Delta$  — BaFCL-screens,  $\blacktriangle$  —  $\text{BaSO}_4/\text{SrSO}_4$ -screens,  $\bullet$  — LaOBr-screens,  $\square$  —  $\text{Gd}_2\text{O}_2\text{S}$ -screens,  $\circ$  —  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ -screens and  $\square$  —  $\text{CaWO}_4$ -screens.

Fine. These lines indicate two cases where sensitivity increases are achieved with equal fractional increases of energy absorption and light-yield. It is very interesting to see that many of the screen-film systems are located along one or the other of these two lines.

In the previous chapter, it was found that the sensitivity gains between two sets of screen-film systems are achieved by means of almost equal increases of the energy absorption and light yield. These screen-film systems (Lanex Fine-Lanex Regular and Rarex BG Detail-Rarex BG High speed) are located along the lower solid line.

Sensitivity, light-yield and expected quantum noise. The balance between energy absorption and light-yield to obtain a specific sensitivity is im-

portant, since it affects the ultimate image quality. High light-yield leads to low absorbed x-ray energy, i.e. few x-ray quanta are utilized for production of the film density. This will result in high quantum mottle. If the high light yield is related to large light diffusion, the resolution will be low. If, on the other hand, high energy absorption is adopted, numerous x-ray quanta are utilized for the production of the film density. This results in low quantum mottle. If the high energy absorption is attained by the use of thick screens, light diffusion will be large, which again will result in low resolution capacity.

The resolution capacity of a screen-film system is a complex property influenced by many factors. It is, therefore, not possible, by theoretical considerations alone, to determine the balance between energy absorption and light-yield which gives optimal resolution properties for the screen-film systems.

For the quantum mottle, the situation is different, because there is a direct correlation between the number of x-ray quanta utilized for image formation and the appearance of quantum mottle.

As far as screens with equal phosphor layers are concerned, one can expect that sensitivity gains, by means of enhancements of both energy absorption and light-yield, will involve impairment of the resolution, as well as of the noise properties, of the screen-film systems. A moderate impairment of these two properties can be expected to be less destructive to the overall image quality than would be the case if a drastic reduction of only one of them was made while the other was kept constant. The fact that so many systems in Figure 6 are located along the two solid diagonal lines, indicating equal increases of energy absorption and light-yield, to obtain a sensitivity gain, can be considered as evidence, that this also is the case when put into practice. The weighting, though, between energy absorption and light-yield is different for these two groups of systems. Since the systems along the lower line have a lower light-yield, their quantum mottle can be predicted to be lower than that of the systems of equal sensitivity which are located along the upper line. Or equivalently, at comparable quantum noise levels, the systems belonging to the lower group have higher sensitivity (about 50 %) than those be-

longing to the upper group.

The data points in Figure 6 on the Par Speed calcium tungstate system and the barium sulphate/strontium sulphate system, X-Omatic Regular, enable interesting comparisons. Their sensitivities differ by a factor of two, but, since they have the same light-yield, their quantum noise levels can be predicted to be comparable. The measured noise properties and also the resolution capacities of these two systems have been studied (Holje, 1983 d; Holje and Doi, 1982).

An illustrative example where identical sensitivity is obtained with different combinations of energy absorption and relative light-yield is found among the high sensitive lanthanum oxybromide systems. Here the Titan 923 system, indicated with the upper filled circle, has much higher light-yield, but lower energy absorption, than the Rare Earth system, which is indicated with the lower filled circle. Because of its higher light-yield, the Titan 923 system is expected to exhibit the higher level of quantum mottle: about 1.3 times higher than that of the Rare Earth system. The validity of these predictions will be shown in connection with evaluations of the noise properties of the screen-film systems (Holje, 1983 d).



## REFERENCES

Arnold B.A., Eisenberg H. and Bjärngard B.E., 1978.

Measurements of reciprocity law failure in green-sensitive X-ray films.  
Radiology 126:493-498.

Buchanan R.A., Finkelstein S.I. and Wickersheim K.A., 1972.

X-Ray exposure reduction using rare-earth oxysulfide intensifying screens.  
Radiology 105:185-190.

Castle J.W., 1977.

Sensitivity of radiographic screens to scattered radiation and its relationship to image contrast.  
Radiology 122:805-809.

E. I. L., 1965.

Manual for ionization chambers Models A37A, B37A, D37C, Instruction manual.  
Electronic Instruments Limited

Hamilton J.F., 1966.

Reciprocity, intermittency, and low-temperature exposure effects.  
In The Theory of the Photographic Process, eds. Mees C.E.K. and James T.H.,  
MacMillan Co., New York.

Holje G., 1977.

Image quality study of screen-film systems with various chemical composition.  
Unpublished data.

Holje G., 1983 a.

Photon attenuation by intensifying screens used in diagnostic radiology.  
CODEN Report LUNFD6 (NFRA-3033) / LUMEDW (MERI-3033), Dept. of Radiation  
Physics, Lund University, Lund, Sweden.

Holje G., 1983 b.

Energy absorption in radiographic intensifying screens.

CODEN Report LUNFD6 (NFRA-3034) / LUMEDW (MERI-3034), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 d.

Radiographic mottle in screen-film systems used in diagnostic radiology.

CODEN Report LUNFD6 (NFRA-3036) / LUMEDW (MERI-3036), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 f.

Coefficients for converting X-ray exposure to photon fluence and energy fluence.

CODEN Report LUNFD6 (NFRA-3038) / LUMEDW (MERI-3038), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., Svahn G. and Holm T., 1973.

Investigation of X-ray exposure rates occurring behind the patient in various diagnostic examinations.

Unpublished data.

Holje G. and Svahn G., 1974.

Investigation of intensifying screens for X-ray cassettes (in Swedish, English summary).

The Swedish Institute for the Planning and Rationalization of Health and Social Welfare Services Report 6030:9.

Holje G., Svahn G., Hårdstedt C., Ramnhagen A., Öberg A. and Forsberg H., 1977.

Intensifying screens for X-ray cassettes, performance, usability, etc. (in Swedish, English summary).

The Swedish Institute for the Planning and Rationalization of Health and Social Welfare Services Publication S 67.

Holje G. and Persson S., 1980.

The sensitivity of screen-film systems (in Swedish).

The Swedish Radiation Protection Agency, Publication SSI:1980-33.

Holje G. and Doi K., 1982.

MTF's and Wiener spectra of radiographic screen-film systems. Part 2.

Sensitivity, sensitometry, resolution and noise characteristics of new screen-film systems.

U.S. Department of Health and Human Services, Publication FDA 82 -8187,

Bureau of Radiological Health, Rockville, Maryland 20857, U.S.A.

Johns H.E. and Cunningham J.R., 1969.

The physics of radiology, Third edition: 609-610.

Charles C. Thomas Publisher, Springfield, Illinois, U.S.A.

Mika N. and Reiss K.H., 1973.

Tabellen zur Röntgendiagnostik, Teil 1.

Siemens Aktiengesellschaft, Erlangen, Fed. Rep. of Germany.

Rao G.U.V., Fatouros P.P. and James A.E., 1978.

Physical Characteristics of modern radiographic screen-film systems.

Investigative Radiology 13:460-468.

Reynolds J., Skucas J. and Gorski J., 1976.

An evaluation of screen-film speed characteristics.

Radiology 118:711-713.

Rossi R.P., Hendee W.R. and Ahrens C.R., 1976.

An evaluation of rare-earth screen-film combinations.

Radiology 121:465-471.

Schwarz G.S., 1961.

Unit-step radiography.

Charles C. Thomas Publisher, Springfield, Illinois, U.S.A.

Shuping R.E. and Judy P.F., 1977.

Energy absorbed in calcium tungstate X-ray screens.

Medical Physics 4(3):239-243.

Sprawls P., 1977.

The physical principles of diagnostic radiology : 232.

University Park Press, Baltimore, Maryland 21202, U.S.A.

Stevens A.L.N. and Pingault F., 1975.

BaFCl:Eu<sup>2+</sup>, A new phosphor for X-ray intensifying screens.

Philips Res. Reports 30:277-290.

Svahn G., 1977.

Diagnostic X-ray spectra. Doctoral dissertation. Dept. of Radiation Physics, University of Lund, Lund, Sweden.

Venema H.W., 1979.

X-Ray absorption, speed and luminescent efficiency of rare-earth and other intensifying screens.

Radiology 130:765-771.

Vyborny C.J., 1976.

The speed of radiographic screen film systems as a function of X-ray energy and its effect on radiographic contrast. Doctoral dissertation. The University of Chicago, Chicago, Illinois, U.S.A.

Vyborny C.J., Metz C.E., Doi K. and Rossmann K., 1977.

Screen film system speed: Its dependence on X-ray energy.

Radiology 125:811-816.







Dokumentutgivare  
Inst för radiofysik  
Handläggare

Dokumentnamn  
CODEN Report  
Utgivningsdatum  
April 1983

Dokumentbeteckning  
3036  
Ärendebeteckning

Författare

Gunnilla Holje

Dokumenttitel och undertitel

RADIOGRAPHIC MOTTLE IN SCREEN-FILM SYSTEMS USED IN DIAGNOSTIC RADIOLOGY  
An evaluation of the noise-equivalent number of absorption events and its correlation to Wiener spectral data at very low spatial frequency. A survey of screen-film systems with fluorescent layers of various chemical compositions under exposure conditions simulating those occurring in various diagnostic X-ray examinations.

Referat (sammandrag)

Noise equivalent absorption has been determined in twenty-two intensifying screens with seven different phosphor compositions. The investigation also includes determinations of noise-equivalent number of absorption events when these screens are exposed together with medium-sensitive X-ray films. The inverses of these numbers are used for predictions of the quantum mottle. A comparison with measured radiographic mottle reveals that the relative quantum mottle in screen-film systems can be predicted with good accuracy. It is found, however, that special attention must be paid to the quantification of structure mottle. The influence of radiation quality on noise equivalent absorption and predicted quantum mottle is investigated. Good agreement is found between the variations in predicted quantum mottle and measured radiographic mottle. A comprehensive demonstration is made of the relationship between sensitivity, noise equivalent absorption and quantum mottle in the screen-film systems. It is found that the new screen-film systems can provide sensitivities, which are between 1.6 and 3.7 times higher than that of a medium sensitive calcium tungstate system, without any increase in quantum mottle.

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Indextermer (ange källa)

Omfång

Övriga bibliografiska uppgifter

Språk

Sekretessuppgifter

ISSN

ISBN

Dokumentet kan erhållas från

Mottagarens uppgifter

Inst för radiofysik vid Lunds universitet  
Lasarettet  
S-221 85 LUND

Pris

SIS-  
DB 1

DOKUMENTDATABLAD enligt SIS 62 10 12

Blankett LU 11:25 1976-07



# RADIOGRAPHIC MOTTLE IN SCREEN-FILM SYSTEMS USED IN DIAGNOSTIC RADIOLOGY

An evaluation of the noise-equivalent number of absorption events and its correlation to Wiener spectral data at very low spatial frequency. A survey of screen-film systems with fluorescent layers of various chemical compositions under exposure conditions, simulating those occurring in various diagnostic x-ray examinations

Gunnila Holje

Lund 1983





## CONTENTS.

|                                                                                                                                                                                   | Page |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 1 INTRODUCTION .....                                                                                                                                                              | 1    |
| 2. CALCULATIONS OF THE NOISE-EQUIVALENT ABSORPTION IN INTENSIFYING SCREENS AND DETERMINATIONS OF THE NOISE-EQUIVALENT NUMBER OF ABSORPTION EVENTS IN THE SCREEN-FILM SYSTEMS..... | 6    |
| 2.1 The energy absorption                                                                                                                                                         | 6    |
| 2.2 Absorbed energy distributions                                                                                                                                                 | 8    |
| 2.3 The mean energy deposition                                                                                                                                                    | 10   |
| 2.4 Noise-equivalent number of absorption events; the quantum number.                                                                                                             | 11   |
| * The correlation between the Wiener spectral value at low frequencies and the noise-equivalent number of absorption events.                                                      | 12   |
| 2.5 The influence of radiation quality on the noise-equivalent number of absorption events.                                                                                       | 12   |
| * The correlation between the Wiener spectral value at low frequencies and the noise-equivalent number of absorption events at various radiation qualities.                       | 13   |
| 2.6 Noise-equivalent absorption.                                                                                                                                                  | 13   |
| 2.7 The influence of radiation quality on the noise-equivalent absorption.                                                                                                        | 14   |
| 3. RESULTS AND DISCUSSION.....                                                                                                                                                    | 15   |
| 3.1 The mean energy deposition.                                                                                                                                                   | 15   |
| 3.2 The noise-equivalent absorption at 80 kV filtered with 20 mm aluminium.                                                                                                       | 15   |
| * Noise-equivalent absorption versus energy absorption; the influence of the chemical composition of the phosphor.                                                                | 17   |
| 3.3 The influence of radiation quality on the noise-equivalent absorption.                                                                                                        | 19   |

(cont.)

|                 |                                                                                                                     |    |
|-----------------|---------------------------------------------------------------------------------------------------------------------|----|
| 3.4             | The noise-equivalent number of absorption events in the screen-film systems at 80 kV filtered with 20 mm aluminium. | 21 |
| *               | Noise-equivalent number of absorption events evaluated from measured noise properties, the screen numbers.          | 21 |
| *               | The correlation between quantum numbers and screen numbers.                                                         | 24 |
| *               | The influence of structure mottle on the correlation between quantum numbers and screen numbers.                    | 26 |
| 3.5             | The influence of radiation quality on the quantum mottle.                                                           | 30 |
| *               | The correlation between predicted and measured quantum mottle at various radiation qualities.                       | 31 |
| 3.6             | Sensitivity, noise-equivalent absorption and quantum mottle.                                                        | 32 |
| REFERENCES..... |                                                                                                                     | 37 |

## 1. INTRODUCTION

The radiographic mottle together with the resolution capacity of a screen-film system are recognized as the fundamental physical properties which affect the visibility of objects being radiographed. Jures and Rudinger (1938) treated the subject of radiographic mottle in a paper entitled "On problems of graininess of radiographs prepared with intensifying screens". Rose (1953) documented his experiences in the field in a publication with the descriptive title "Quantum and Noise Limitations of the Visual Process". In "An experimental study of the mottle produced by x-ray intensifying screens", Cleare et al.(1962) described an investigation of the various possible sources of radiographic mottle. Rossmann (1963) showed clearly that this mottle is composed of film graininess and screen mottle. The film graininess was shown to be small compared to the screen mottle and therefore generally has little influence on the total radiographic mottle. Of the two components constituting the screen mottle, namely quantum mottle and screen structure mottle, the quantum mottle was regarded as being the dominating one. The validity of this statement on current screens will be judged from the results achieved in the present investigation.

It has been shown (Rossmann, 1962 a, b, 1963, 1968) that the screens ability to absorb x-ray quanta is the fundamental physical screen characteristic affecting the quantum mottle. Once the quanta are absorbed, the optical characteristics of the screens come in as a secondary effect, as they determine the sharpness by which the resulting light bursts are imaged. By regarding the fluctuations of the absorbed x-rays as a "white noise" input to the screen-film system and the quantum mottle as the resulting output, Rossmann expressed the Wiener spectrum of the quantum mottle as:

$$\Phi(\nu) \sim G^2 \cdot (1/Nq) \cdot |A(\nu)|^2 \quad (1)$$

where

|            |                                                                                 |
|------------|---------------------------------------------------------------------------------|
| $\nu$      | is the spatial frequency                                                        |
| $G$        | is the film gradient at average density                                         |
| $Nq$       | is the average number of x-ray quanta absorbed per unit area of the screen, and |
| $ A(\nu) $ | is the modulation transfer function of the screen-film system                   |

The characterization of the quantum mottle, not only by a single number but by means of its Wiener spectrum, was hereby established. The connection between the optical characteristics of a screen-film system and the Wiener spectrum of the quantum mottle was illustrated by Rossmann (1962,a) in a publication where he used the Wiener spectrum of the quantum mottle to determine the relative modulation transfer function of some radiographic systems. A similar method was used by Doerner (1962) for determinations of the modulation transfer function of an optical lens.

Equation 1 shows that the optical characteristics of the screen-film system only have a degrading effect ( $A(\nu) \leq 1.0$ ) on the appearance of the quantum mottle. A characterization of the quantum mottle by means of the number of x-ray quanta absorbed, will, therefore, yield noise levels which represent the upper possible limits of the quantum noise.

Research on quantum mottle was intensified during the 1970's. The reason for this was that new x-ray phosphors with improved conversion efficiency were introduced (Buchanan et al., 1973; Stevels and Pingault, 1975). The use of screens made of such phosphors resulted in as much as a ten-fold sensitivity gain when compared to medium sensitive calcium tungstate systems. If this sensitivity gain were solely due to an increase in the screens' conversion efficiency, a drastic increase in the quantum mottle could be expected. It has been shown, however, that the increased sensitivity of the new screen-film systems is achieved partly by increased energy absorption, and partly by the increased light-yield of the new screens (Holje, 1983 c). It will be shown here that it is possible to roughly predict the

resulting increase in radiographic mottle from information on how a sensitivity gain has been achieved.

Wagner and Weaver (1975, 1977), Wagner (1977 a), Doi and Imhof (1977), Rao and Fatouros (1979) and Holje and Doi (1982), among others, have devoted special attention to the quantum mottle in the new screen-film systems. Some new systems have hereby been shown to exhibit relatively high noise levels when exposed with conventional blue sensitive film. Provided, however, that this high noise is due to quantum mottle, it can be reduced if films of lower sensitivity are used. Holje et al. (1977) and Holje and Doi (1982) have shown that proper combinations of new screens and films can provide systems with 1.6 to 2.5 times the sensitivity of conventional calcium tungstate systems, with the same or better image quality. These estimations were based on the inverse relationship existing between the appearance of quantum mottle and the average number of x-ray quanta absorbed per unit screen area (see Equation 1).

Wagner (1977) and Sandrik and Wagner (1982) employ the quantities "noise-equivalent quanta" and "detective quantum efficiency" (Dainty and Shaw, 1974), as absolute measures of image quality. These two quantities, which are frequency dependent, are derived from the image characteristics of the screen-film system. At low frequencies, these quantities correspond to the quantities, "noise-equivalent number of absorption events" and "noise-equivalent absorption", which are determined in this investigation from the energy absorption properties of the screen-film system. These latter quantities, however, only apply to quantum mottle, while those determined by Wagner also include the screens' structure mottle. Since the structure mottle may be considerable, this can give rise to large differences between values determined by the two methods. It will be shown in the present study that the structure mottle in some systems can even exceed the quantum mottle.

In the paper: "Absorption and noise in x-ray phosphors", Swank (1973) defined a quantity called "noise-equivalent absorption". This quantity was shown to have a simple relationship to the signal-to-noise ratio. The noise-equivalent absorption was determined from the energy absorption properties in five x-ray phosphors of various thicknesses. Swank's in-



vestigation only treats phosphors and does not include any determinations of the noise-equivalent number of absorption events, nor any records of the resulting noise or signal-to-noise ratios, which are quantities of great importance for screen-film systems.

The work presented here includes determinations of the noise-equivalent absorption in twenty-two intensifying screens made of seven different phosphors, Table 1. The investigation also includes determinations of the noise-equivalent number of absorption events needed to produce a film density of 1.0, when these screens are exposed together with medium-speed blue or green sensitive x-ray film. The sensitivities, resolutions and radiographic mottles of these screen-film systems have been determined and been presented in other publications (Holje, 1983 c, g; Holje and Doi, 1982). Having access to data on the noise-equivalent number of absorption events, and also to experimentally determined radiographic mottle enables important comparisons of these two quantities (Holje and Westrup, 1978). It allows an examination of the validity of noise predictions by means of the noise-equivalent number absorption events determined here. It may also allow an evaluation of the accuracy of the empirical expression for the Wiener spectral values of quantum mottle in Equation 1. In addition, a comparison between Wiener spectral values of the total screen mottle (quantum and structure mottle) and the number of absorption events in the screens (quantum mottle only) can provide possibilities to determine if the screens contain a perceivable level of structure mottle.

The noise-equivalent absorption and the noise-equivalent number of absorption events in the screens have been evaluated at twenty different radiation qualities. These were produced at the x-ray tube potentials 60, 80, 100 and 120 kV and with 5, 10, 15, 20 and 25 mm aluminium filter. The radiation qualities have been discussed elsewhere (Holje, 1983 f). The incident radiation distribution is of particular interest, since the screens investigated are made of phosphors with different chemical compositions. Having quite different energy absorption characteristics (Holje, 1983 b), these screens can be predicted to exhibit different quantum noise characteristics. Barnes (1976) has shown that these differences are large enough to be recorded on the films. From calculations of the noise-equivalent number of absorption events at various radiation qua-

TABLE 1.

| Manufac-<br>turer | Trade name        | Phosphor                                                                              | Dominating<br>K-abs/keV | Film |
|-------------------|-------------------|---------------------------------------------------------------------------------------|-------------------------|------|
| Agfa-<br>Gevaert  | M.R. 50           | LaOBr:Tb                                                                              | 38.93                   | XRP  |
|                   | M.R. 200          | "                                                                                     | "                       | "    |
|                   | M.R. 400          | "                                                                                     | "                       | "    |
|                   | M.R. 600          | "                                                                                     | "                       | "    |
| CAWO              | SE 2              | LaOBr:Tb                                                                              | 38.93                   | XRP  |
|                   | SE 4              | "                                                                                     | "                       | "    |
|                   | SE 6              | "                                                                                     | "                       | "    |
| DuPont            | Cronex Par Sp.    | CaWO <sub>4</sub>                                                                     | 69.53                   | XRP  |
|                   | Cronex Quanta II  | BaFCl:Eu                                                                              | 37.44                   | "    |
| Fuji              | Grenex G-4        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   | OG   |
|                   | Grenex G-8        | "                                                                                     | "                       | "    |
| G.E.              | Blue Max 1        | LaOBr:Tb                                                                              | 38.93                   | XRP  |
|                   | Blue Max 2        | "                                                                                     | "                       | "    |
| Ilford            | Rare Earth        | LaOBr:Tm                                                                              | 38.93                   | XRP  |
| Kodak             | X-Omatic Reg.     | BaSO <sub>4</sub> :Eu/SrSO <sub>4</sub> :Eu                                           | 37.44/16.11             | XRP  |
|                   | Lanex Fine        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   | OG   |
|                   | Lanex Reg.        | Gd <sub>2</sub> O <sub>2</sub> S:Tb/La <sub>2</sub> O <sub>2</sub> S:Tb <sup>1)</sup> | 50.24/38.93             | "    |
| Philips           | Type 4360         | BaFCl:Eu                                                                              | 37.44                   | XRP  |
|                   | Type 6359         | "                                                                                     | "                       | "    |
| Siemens           | Rubin Super       | CaWO <sub>4</sub>                                                                     | 69.53                   | XRP  |
|                   | Titan 923         | LaOBr:Tb                                                                              | 38.93                   | "    |
| 3M                | Trimax Alpha 4    | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   | OG   |
|                   | Trimax Alpha 8    | "                                                                                     | "                       | "    |
| U.S.<br>Radium    | Rarex BG Detail   | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>2)</sup>  | 50.24/17.04             | OG   |
|                   | Rarex BG Mid Sp.  | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>3)</sup>  | 50.24/17.04             | "    |
|                   | Rarex BG High Sp. | "                                                                                     | "                       | "    |
|                   | Rarex B Mid Sp.   | Y <sub>2</sub> O <sub>2</sub> S:Tb                                                    | 17.04                   | XRP  |

The films are manufactured by Eastman Kodak Co.

1) 93 %/ 7 % by weight 2) 60 %/ 40 % by weight, 3) 75 %/ 25 % by weight.

lities, predictions can be made of the resulting noise variations. To verify these predictions, the investigation also includes evaluated Wiener spectra of screen-film systems based on different phosphors at different radiation qualities.

A comprehensive demonstration will be made of the relationship between sensitivity, noise-equivalent absorption and quantum mottle in the screen-film systems. This demonstration will be used for predictions of the sensitivity increases which can be obtained with the new screen-film systems provided that their quantum mottles are not allowed to be higher than that in a medium sensitive calcium tungstate system.

## 2. CALCULATIONS OF THE NOISE-EQUIVALENT ABSORPTION IN INTENSIFYING SCREENS AND DETERMINATIONS OF THE NOISE-EQUIVALENT NUMBER OF ABSORPTION EVENTS IN THE SCREEN-FILM SYSTEMS

The noise-equivalent number of absorption events determined in this investigation is defined in Section 2.4 as the number of mean energy depositions, which are needed per unit screen area for production of film density 1.0. These are determined from the quotient between the total energy imparted to the screens and the mean value of the individual energy depositions (Swank, 1973). The noise-equivalent number of absorption events per incident photon of mean energy is defined in Section 2.6 as the noise-equivalent absorption.

Determinations of the magnitude of the mean energy deposition require knowledge of the absorbed energy distributions. These are determined in Chapter 2.2 by use of a simple model for the energy absorption processes.

### 2.1 The energy absorption.

A simple model for the energy absorption processes was utilized to determine the absorbed energy distributions in the screens. A detailed description of this model is given in connection with evaluations of the energy absorption in the screens (Holje, 1983 b). The absorption of internally produced K x-rays is of specific interest for noise evaluations. The model treats this as separate energy deposition events. Determined by

the attenuation properties, however, an entire range of K x-ray mean free path lengths exists in the screens' phosphors. It is, therefore, obvious that the spatial connection between the primary and secondary interaction events can not be represented by a single number. Therefore, the problem of immediate interest here whether the absorption K x-rays should be treated as a separate event or be added to the primary absorption event, does not have a simple solution. K x-ray absorption events within a "certain distance" from the primary event give rise to electron tracks which presumably are spatially so close to the electron track arisen in the primary event, that their final effect on the exposed film is equivalent to only one large absorption event. K x-ray absorption events beyond this distance, on the other hand, can be expected to affect the film as separate light-bursts, disconnected from those arisen in the primary event. Up till now much effort has not been devoted to determinations of the noise equivalent number of absorption events. The introduction of new screens made of phosphors with higher conversion efficiencies than those of the conventional calcium tungstate screens stimulated a renewed interest in these questions, but very much still remains to be done in the research on noise and its background. There are no publications for example, so far, on any investigation concerning the critical distance mentioned above, within which the primary absorption and the related K x-ray absorption events can be treated as one event. Being without such data to support any theories, the approach taken here has been to treat K x-ray absorption events as independent events.

An experimental investigation of the dependence of noise Wiener spectra on the incident photon energy shows a decrease of the Wiener spectral values at photon energies exceeding that of the K-absorption of the high Z-element of the phosphor (Vyborny et al., 1982). This confirms that at least a part of the K x-ray absorption events should be treated as separate energy absorption events. The assumption that all K x-ray absorption events are independent may agree fairly well with the actual case for screens where the K x-rays have a long mean free path, as is the case for the calcium tungstate screens (Holje, 1983 e). For screens, on the other hand, where the K x-rays reach only short distances from the primary absorption event, as in the yttrium oxysulphide screens (Holje, 1983 e),

this approach may be less accurate. For these screens, therefore, calculations of the noise-equivalent absorption were made also in the case where the K x-ray absorption is regarded as an addition to the primary absorption event.

## 2.2 Absorbed energy distributions.

The energy absorbed per unit screen area for production of the film density 1.0,  $C_{x,y}$ , has been determined from the energy absorption and sensitivity of the screen-film systems (Holje, 1983 c):

$$C_{x,y} = \int_{h\nu_{\min}}^{h\nu_{\max}} B(h\nu) \cdot \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu = \int_{h\nu_{\min}}^{h\nu_{\max}} \left(\frac{dC(h\nu)}{dh\nu}\right)_{x,y} dh\nu \quad (2)$$

where

$B(h\nu)$  is the energy absorption by the screens of photons with energy  $h\nu$  (Holje, 1983 b),

$\int_{h\nu_{\min}}^{h\nu_{\max}} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu$  is the energy fluence of photons needed to produce the net density 1.0 of the films at the radiation distributions produced at  $x$  kV filtered with  $y$  mm aluminium (Holje, 1983 c),

and  $h\nu_{\min}$  and  $h\nu_{\max}$  are the lowest and highest photon energies.

The parameter  $\left(\frac{dC(h\nu)}{dh\nu}\right)_{x,y}$  in Equation 2 expresses the differential distribution of the energy absorbed per unit screen area with respect to the incident photon energy. Of importance in this investigation, however, is the differential distribution of the energy absorbed in the screens in respect to the magnitude of the absorption events,  $\left(\frac{dC(E)}{dE}\right)_{x,y}$ . This distribution is defined by:

$$\left(\frac{dC(h\nu)}{dh\nu}\right)_{x,y} = \left(\frac{dC(E)}{dE}\right)_{x,y} \cdot \frac{dE}{dh\nu} \quad (3)$$

where  $E$  is the magnitude of the energy deposition event (Holje, 1983b).



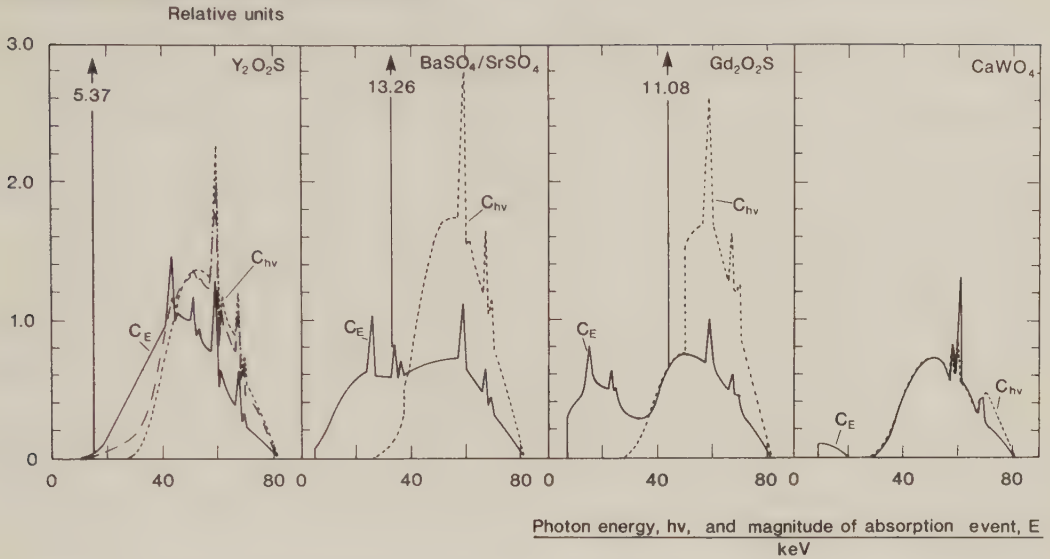


Figure 1. Differential absorbed energy per unit area of screens with different chemical compositions. Incident photon distribution is produced at 80 kV filtered with 20 mm aluminium.-----  $C_{hv}$ , is the absorbed energy distribution in respect to incident photon energy and —  $C_E$ , is the distribution in respect to the magnitude of the absorption event. (--- refers to the case where K x-ray absorption and primary absorption are treated as one event).

An illustration of the two differential distributions is given in Figure 1. The incident energy fluence of photons is produced at the x-ray tube potential 80 kV filtered with 20 mm aluminium. The differential distributions of the energy absorbed per unit screen area in respect to the incident photon energy and in respect to the magnitude of the energy deposition event are illustrated in four intensifying screens with different chemical compositions. For the yttrium oxysulphide screens, two differential distributions are plotted versus the magnitude of the absorption event. One applies to the case where the absorption of internally produced K x-rays is treated as a separate event, which is in agreement with the other screens. The other applies to the case where the K x-ray absorption and the primary absorption are treated as one event.

It is obvious from Figure 1 that substantial differences exist between the differential energies absorbed when they are treated in respect to incident photon energy and when they are treated in respect to the magni-

tude of the absorption event. This is due to the production and subsequent escape of the K x-rays of the high Z-element of the phosphor. The difference becomes especially pronounced when the absorption of this characteristic radiation is treated as a separate event. The distribution of the energy absorbed per unit screen area is thus composed of a full energy absorption distribution, a K x-ray energy escape distribution and a K x-ray energy absorption peak. That distribution of the energy absorbed in the  $Y_2O_3$ -screens, which is the only case where the K x-ray absorption and the primary absorption are treated as one event, is composed of only a full energy absorption distribution and a K x-ray energy escape distribution. The discrepancy between this latter distribution and that versus incident photon energy is very small. This is due to the high probability for absorption of K x-ray energy that exists in these screens, (Holje, 1983 e).

Figure 1 shows that there are substantial differences in the absorbed energy distribution in screens with different chemical compositions. This is a result of their different absorption characteristics. Since these distributions are employed in the calculations of the mean value of the energy deposition events, one realizes that the phosphor's chemical composition will be decisive for this mean energy.

### 2.3 The mean energy deposition.

The mean energy deposition,  $\bar{E}_{x,y}$ , at x kV filtered with y mm aluminium is determined as the mean value of the individual energy deposition events, E, weighted according to the absorbed energy distribution,  $(\frac{dC(E)}{dE})_{x,y}$ , (Swank, 1973):

$$\bar{E}_{x,y} = \frac{\int_{E_{\min}}^{E_{\max}} E \cdot (\frac{dC(E)}{dE})_{x,y} dE}{\int_{E_{\min}}^{E_{\max}} (\frac{dC(E)}{dE})_{x,y} dE} \quad (4)$$

where  $E_{\min}$  and  $E_{\max}$  are the lowest and highest energy depositions. The double bars in  $\bar{E}_{x,y}$  denote that this is the mean energy of an energy distribution.

This weighting, which favours the higher energy depositions, probably agrees well with the resultant blackening of the film, since a large energy deposition gives rise to a large energy fluence of light-photons, which, when striking the film, give a high energy deposition to the silver bromide grains. Few high-energy depositions give the same result as many low-energy depositions, i.e. developable silver bromide grains.

#### 2.4 Noise-equivalent number of absorption events; the quantum number.

The quotient between the absorbed energy,  $C_{x,y}$ , in Equation 2 and the mean energy deposition  $\bar{E}_{x,y}$ , determined in Equation 4, gives the number of mean energy depositions which are needed per unit screen area for production of film density 1.0. This is the noise equivalent number of absorption events  $(Nq)_{x,y}$ , which will also be called the quantum number in the following.

$$(Nq)_{x,y} = \frac{C_{x,y}}{\bar{E}_{x,y}} = \frac{\int_{h\nu \min}^{h\nu \max} B(h\nu) \cdot \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{\bar{E}_{x,y}} = B_{x,y} \cdot \frac{\bar{h\nu}_{x,y}}{\bar{E}_{x,y}} \cdot \phi_{x,y} \quad (5)$$

where

$$B_{x,y} = \frac{\int_{h\nu \min}^{h\nu \max} B(h\nu) \cdot \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu \min}^{h\nu \max} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}$$

is the energy absorption by the screens at the radiation quality produced at x kV filtered with y mm aluminium (Holje, 1983 b),

$$\bar{h\nu}_{x,y} = \frac{\int_{h\nu \min}^{h\nu \max} h\nu \cdot \left(\frac{d\phi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu \min}^{h\nu \max} \left(\frac{d\phi}{dh\nu}\right)_{x,y} dh\nu}$$

is the mean energy of the incident photon fluence distribution\*,

$$* \quad \bar{\bar{h\nu}}_{x,y} = \frac{\int_{h\nu \min}^{h\nu \max} h\nu \cdot \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu \min}^{h\nu \max} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}$$

corresponds to the mean energy of the incident energy fluence distribution of photons.

$$\phi_{x,y} = \int_{h\nu \text{ min}}^{h\nu \text{ max}} \left( \frac{d\phi}{dh\nu} \right)_{x,y} dh\nu$$

is the incident photon fluence at x kV filtered with y mm aluminium needed to produce the net density 1.0 of the films, and

$$\int_{h\nu \text{ min}}^{h\nu \text{ max}} \left( \frac{d\Psi}{dh\nu} \right)_{x,y} dh\nu$$

is the corresponding energy fluence.

The correlation between the Wiener spectral value at low frequencies and the noise equivalent number of absorption events. At very low frequencies where the modulation transfer function of the screen-film system is very close to unity, Equation 1 will be:

$$\Phi \text{ (low frequencies)} \sim \frac{G^2}{Nq} \quad (6)$$

Equation 6 indicates that only a constant factor, the squared film gradient differs between the Wiener spectral value at low spatial frequencies, and the inverse quantum number. The significance of being able to perform correct calculations of the noise equivalent number of absorption events from the energy absorption characteristics of the screens is therefore obvious.

## 2.5 The influence of radiation quality on the noise-equivalent number of absorption events.

The influence of radiation quality on the noise-equivalent number of absorption events in the different screen-film systems is determined from Equation 5. It has been shown that the absorbed energy per unit screen area for production of the film density 1.0,  $C_{x,y}$ , is constant and independent of the radiation qualities studied here (Holje, 1983 c). The quantum number in a screen-pair at the radiation quality produced at x kV filtered with y mm aluminium,  $(Nq)_{x,y}$ , relative to that at 80 kV filtered with 20 mm aluminium, is then simply:

$$\frac{(N_q)_{x,y}}{(N_q)_{80,20}} = \frac{C_{x,y}}{C_{80,20}} \cdot \frac{\bar{E}_{80,20}}{\bar{E}_{x,y}} = \frac{\bar{E}_{80,20}}{\bar{E}_{x,y}} \quad (7)$$

Equation 7 shows that a simple inverse relationship exists between the quantum number and the mean energy deposition, when a screen-film system is exposed to constant film density at various radiation distributions.

The correlation between the Wiener spectral value at low frequencies and the noise-equivalent number of absorption events at various radiation qualities. If the same film and developing conditions are used, the film gradient,  $G$  in Equation 6, maintains a constant value. Under this condition, the variation with radiation quality of the Wiener spectral value of quantum mottle at low spatial frequencies will be inversely proportional to that of the quantum number. By combining Equations 6 and 7 we get:

$$\frac{\phi(1.fr.)_{x,y}}{\phi(1.fr.)_{80,20}} \sim \frac{(N_q)_{80,20}}{(N_q)_{x,y}} = \frac{\bar{E}_{x,y}}{\bar{E}_{80,20}} \quad (8)$$

Equation 8 shows that the variation of the mean energy deposition is directly determinant for the resulting variation in quantum mottle when a screen-film system is exposed to the same film density at various radiation qualities.

## 2.6 Noise-equivalent absorption.

The noise-equivalent absorption,  $B_N$ , is the number of noise-equivalent absorption events, expressed in Equation 5, per incident mean energy photon:

$$(B_N)_{x,y} = \frac{(N_q)_{x,y} \cdot \bar{h\nu}_{x,y}}{\int_{h\nu \min}^{\infty} \frac{d\psi}{(d\bar{h\nu})_{x,y}} d\bar{h\nu}} = \frac{(N_q)_{x,y}}{\phi_{x,y}} = B_{x,y} \cdot \frac{\bar{h\nu}_{x,y}}{\bar{E}_{x,y}} \quad (9)$$



Equation 9 shows that the noise-equivalent absorption is equal to the energy absorption,  $B_{x,y}$ , multiplied by a factor,  $\frac{\overline{h\nu}}{\bar{E}}$ , which is the ratio between the mean energies of the incident photon fluence and the absorbed energy distribution.

In connection with Figure 1, it was mentioned that the mean energy deposition,  $\bar{E}$ , can be predicted to be different in screens with different chemical composition. Even if their energy absorption might be equal, those screens having the lowest mean energy deposition will therefore exhibit the highest noise-equivalent absorption. The noise-equivalent absorption, is an interesting quantity since it expresses the screens ability to convert incident x-ray quanta into energy absorption events, which are determinant for the quantum mottle. High noise-equivalent absorption is preferable, since it results in a high number of noise-equivalent absorption events and, thus, a low level of quantum mottle.

## 2.7 The influence of radiation quality on the noise-equivalent absorption.

The energy absorption,  $B_{x,y}$ , the factor,  $(\overline{h\nu} / \bar{E})_{x,y}$ , and consequently also the noise-equivalent absorption,  $(B_N)_{x,y}$  in Equation 9, are affected by the chemical composition of the screen phosphor, its thickness and also by the incident radiation quality. When comparing the noise-equivalent absorption in screens made of different phosphors, it is therefore essential to specify the radiation quality. The influence of radiation quality is illustrated here by presenting the noise-equivalent absorption at various radiation qualities relative to that at 80 kV filtered with 20 mm aluminium. Having access to absolute values at the reference radiation quality will then enable getting data on the noise-equivalent absorption at the other radiation qualities.

The relative noise-equivalent absorption is obtained from Equation 9 as:

$$\frac{(B_N)_{x,y}}{(B_N)_{80,20}} = \frac{(N_q)_{x,y}}{\phi_{x,y}} \cdot \frac{\phi_{80,20}}{(N_q)_{80,20}} = \frac{B_{x,y}}{B_{80,20}} \cdot \frac{\overline{h\nu}_{x,y}}{\overline{h\nu}_{80,20}} \cdot \frac{\bar{E}_{80,20}}{\bar{E}_{x,y}} \quad (10)$$

where

$B_{x,y}$  is the energy absorption by the screens at the radiation quality produced at x kV filtered with y mm aluminium (Holje, 1983 b),

$h\nu_{x,y}$  is the mean energy of the incident photon fluence at x kV filtered with y mm aluminium, and

$\bar{E}_{x,y}$  is the mean energy of the absorbed energy distribution at x kV filtered with y mm aluminium.

### 3. RESULTS AND DISCUSSION

Table 2 presents the intensifying screens together with the sensitivity (Holje, 1983 c) and the energy absorption (Holje, 1983 b) which have been evaluated at the radiation quality produced at 80 kV tube potential and with 20 mm aluminium filter.

#### 3.1 The mean energy deposition.

The mean energy deposition,  $\bar{E}$ , in the various screens was calculated according to Equation 4. Data, presented in column 3 of Table 2, are determined at the radiation quality produced at 80 kV filtered with 20 mm aluminium.

Remarkably small variations of the mean energy deposition are found in screens with identical chemical composition. This implies that differences in screen thicknesses are of minor importance compared to differences in the chemical composition. Calcium tungstate screens have the highest mean energy deposition, 52.7 keV, and barium fluorochloride screens the lowest, 38.4 keV, at this radiation quality. Among the "non-calcium tungstate screens," the screens made of a mixture of gadolinium oxysulphide and yttrium oxysulphide have the highest mean energy deposition, 45.8 keV.

#### 3.2 The noise-equivalent absorption at 80 kV filtered with 20 mm aluminium.

The noise-equivalent absorption in the screen-film systems was determined

TABLE 2

Physical properties of screen-film systems at 80 kV and 20 mm Al

| Intensifying<br>screens | Sensitivity<br>$\text{keV} \cdot \text{mm}^2 \times 10^{-7}$ | Energy<br>absorp. | Mean Energy<br>depos./keV | Noise<br>equiv.<br>absorp. | $\overline{h\nu} / \overline{E}$ |
|-------------------------|--------------------------------------------------------------|-------------------|---------------------------|----------------------------|----------------------------------|
| M.R. 50                 | 0.58                                                         | 0.26              | 41.1                      | 0.35                       | 1.38                             |
| M.R. 200                | 1.51                                                         | 0.31              | 41.0                      | 0.43                       | 1.38                             |
| M.R. 400                | 3.10                                                         | 0.28              | 41.1                      | 0.39                       | 1.38                             |
| M.R. 600                | 4.85                                                         | 0.43              | 41.0                      | 0.60                       | 1.38                             |
| Rare Earth              | 3.84                                                         | 0.38              | 41.1                      | 0.53                       | 1.38                             |
| Titan 923               | 3.86                                                         | 0.29              | 41.1                      | 0.40                       | 1.38                             |
| Cronex Quanta II        | 3.41                                                         | 0.31              | 38.4                      | 0.46                       | 1.48                             |
| Type 4360               | 2.10                                                         | 0.26              | 38.4                      | 0.38                       | 1.48                             |
| Type 6359               | 2.89                                                         | 0.34              | 38.4                      | 0.50                       | 1.48                             |
| X-Omatic Regular        | 1.45                                                         | 0.35              | 39.8                      | 0.49                       | 1.43                             |
| Cronex Par Speed        | 0.65                                                         | 0.15              | 52.4                      | 0.17                       | 1.08                             |
| Rubin Super             | 0.14                                                         | 0.18              | 52.9                      | 0.20                       | 1.07                             |
| Grenex G-4              | 1.75                                                         | 0.31              | 42.9                      | 0.41                       | 1.32                             |
| Grenex G-8              | 3.91                                                         | 0.39              | 43.0                      | 0.51                       | 1.32                             |
| Lanex Fine              | 1.18                                                         | 0.27              | 42.9                      | 0.35                       | 1.32                             |
| Lanex Regular           | 4.55                                                         | 0.47              | 44.3                      | 0.60                       | 1.28                             |
| Trimax Alpha 4          | 1.80                                                         | 0.24              | 42.8                      | 0.32                       | 1.33                             |
| Trimax Alpha 8          | 3.75                                                         | 0.39              | 43.1                      | 0.52                       | 1.32                             |
| Rarex BG Detail         | 1.34                                                         | 0.28              | 45.8                      | 0.35                       | 1.24                             |
| Rarex BG Mid Sp.        | 2.56                                                         | 0.41              | 44.6                      | 0.52                       | 1.27                             |
| Rarex BG High Sp.       | 4.43                                                         | 0.50              | 44.7                      | 0.63                       | 1.27                             |
| Rarex B Mid Sp.         | 3.48                                                         | 0.27              | 43.2                      | 0.36                       | 1.32                             |

according to Equation 9. These are accounted for in column 4 of Table 2. It is obvious that all new screens have higher noise-equivalent absorptions than the two calcium tungstate screens incorporated in the study. It is shown in the following text that this is a combined effect of their higher energy absorption and their lower mean energy deposition.

Noise-equivalent absorption versus energy absorption; the influence of the chemical composition of the phosphor. In Figure 2, the noise-equivalent absorption is plotted versus the energy absorption for the screens investigated. The diagonal lines indicate the ratios,  $\overline{h\nu}/\overline{E}$ , of the mean energy of the incident photon fluence to those of the absorbed energy distributions. These are the mean values for all screens with the same chemical composition. The ratios for the individual screens are listed in column 5 of Table 2.

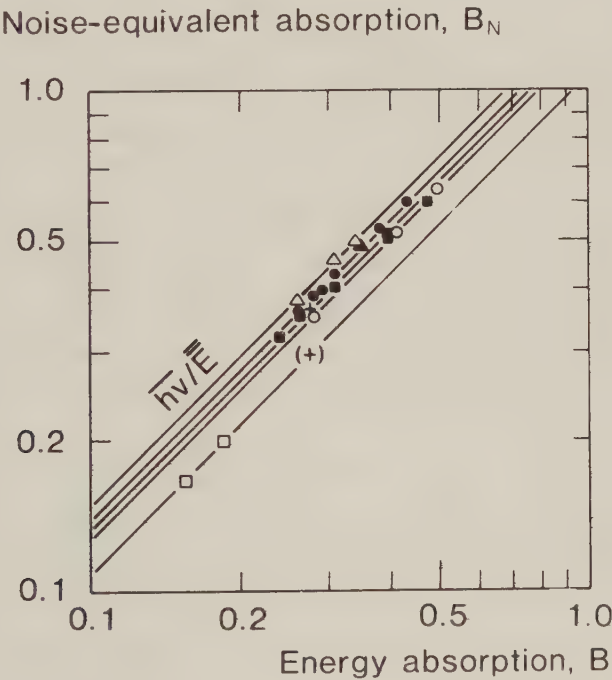


Figure 2. Noise-equivalent absorption versus energy absorption at 80 kV filtered with 20 mm aluminium. The diagonal lines indicate ratios between incident mean photon energy and the mean energy deposition in screens of different chemical compositions. + —  $\text{Y}_2\text{O}_2\text{S}$ -screens,  $\Delta$  —  $\text{BaFCl}$ -screens,  $\blacktriangle$  —  $\text{BaSO}_4/\text{SrSO}_4$ -screens,  $\bullet$  —  $\text{LaOBr}$ -screens  $\blacksquare$  —  $\text{Gd}_2\text{O}_2\text{S}$ -screens,  $\circ$  —  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ -screens  $\square$  —  $\text{CaWO}_4$ -screens. (+) —  $\text{Y}_2\text{O}_2\text{S}$ -screens (K x-ray abs.add. to prim. event).

According to Figure 2 and Table 2, the energy ratios  $\overline{h\nu}/\overline{E}^*$  of the new intensifying screens are significantly higher than those of the calcium tungstate screens. This is due to the magnitude of the mean energy deposition, which previously was shown to be much lower in the new screens. This property of the new screens is advantageous. Figure 2 shows that this has as the consequence that new screens, with the same energy absorption as calcium tungstate screens, can provide almost 1.4 times higher noise-equivalent absorption.

Figure 2 and Table 2 also show that the energy absorption in the new screens is considerably higher than that in the calcium tungstate screens. This is not due to any substantial differences in screen thickness, since the thickness of the two pairs of calcium tungstate screens agrees with that of the thinnest screen pairs made of the new phosphors (Holje, 1983 a). The high efficiency of the new screens to absorb incident photon energy is rather a result of the high mass energy absorption coefficients existing in these screens at the radiation quality employed (Holje, 1983 b). It has been shown that the energy absorption in screens with barium, lanthanum or gadolinium as high Z-element is about 1.6 times higher than that in calcium tungstate screens of equivalent thickness (Holje, 1983 b). This, together with the lower mean energy deposition, gives noise-equivalent absorptions in the new screens which may exceed those of calcium tungstate screens of equal thickness by a factor of 2\*\*. This is shown in Figure 3, where the noise-equivalent absorptions in the screen pairs are plotted versus their thicknesses. The two lines are fitted by linear regression analysis to the data points of lanthanum oxybromide screens and gadolinium oxysulphide screens. This presentation gives a clear picture of the favourable noise-equivalent absorption characteristics existing in most of the new phosphor screens. Due to their higher noise-equivalent absorption, these screens must have a much higher potential than the

\*  $h\nu$  is equal to 56.8 keV at the radiation quality produced at 80 kV filtered with 20 mm aluminium.

\*\*Due to an approximation made in the calculations, the energy absorptions in yttrium oxysulphide screens and calcium tungstate screens are underestimated by about 3 %, and those in the other screens by about 10 % (Holje, 1983 b). This results in noise-equivalent absorptions in new screens which, in comparison to the calcium tungstate screens, are even higher than the factor of 2.



### Noise equivalent absorption

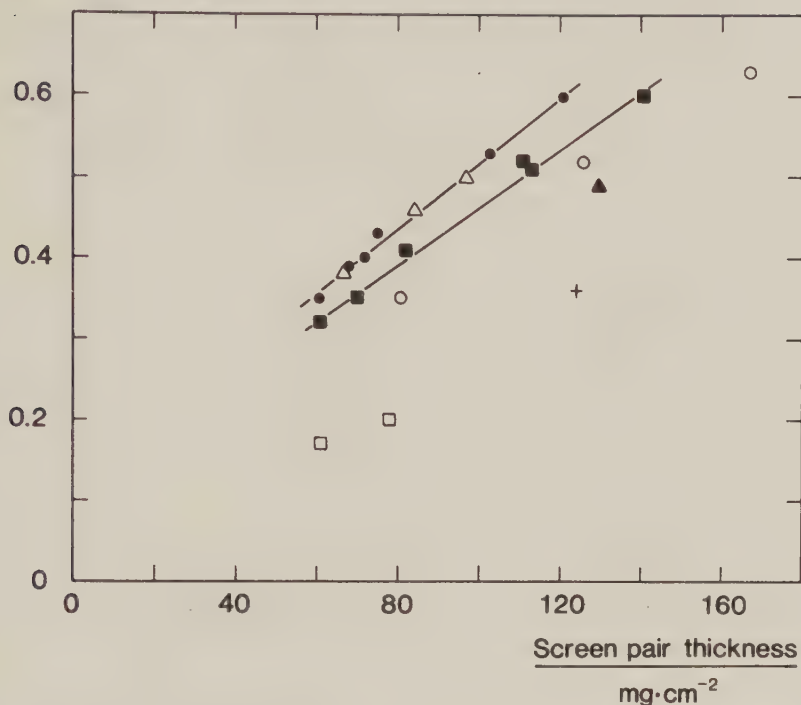


Figure 3. The noise-equivalent absorption in the screen pairs at 80 kV filtered with 20 mm aluminium versus their thicknesses. + —  $\text{Y}_2\text{O}_3\text{S}$ -screens,  $\Delta$  —  $\text{BaFCl}$ -screens,  $\blacktriangle$  —  $\text{BaSO}_4/\text{SrSO}_4$ -screens,  $\bullet$  —  $\text{LaOBr}$ -screens,  $\blacksquare$  —  $\text{Gd}_2\text{O}_2\text{S}$ -screens,  $\circ$  —  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ -screens,  $\square$  —  $\text{CaWO}_4$ -screens. The diagonal lines are fitted by linear regression analysis to the values of  $\text{LaOBr}$ -screens and  $\text{Gd}_2\text{O}_2\text{S}$ -screens, respectively.

calcium tungstate screens to produce images with low quantum mottle.

### 3.3 The influence of radiation quality on the noise-equivalent absorption.

Figure 4 shows the influence of radiation quality on the noise-equivalent absorption in the screen pairs investigated. Data are normalized to those achieved at the radiation quality produced at 80 kV filtered with 20 mm aluminium (Table 2). The radiation qualities employed are produced at 60, 80, 100 and 120 kV filtered with 5-to -25 mm aluminium.

Due to their similar variations in noise-equivalent absorption, all screen-film systems with the same high atomic phosphor element(s) are treated as one group, and their mean values are shown in Figure 4. At the

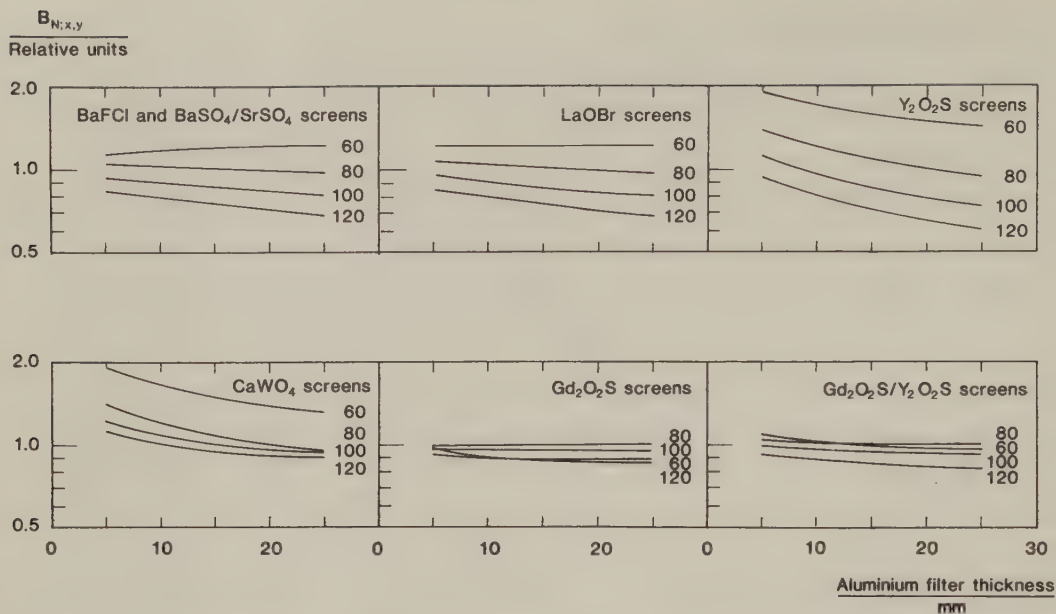


Figure 4. Noise-equivalent absorption in intensifying screens of different chemical compositions at various incident radiation distributions, relative to that at 80 kV filtered with 20 mm aluminium.  $x$  denotes the x-ray tube potential and  $y$  the aluminium filter thickness.

lowest radiation qualities, data on individual screen pairs differ from the mean values by only  $\pm 5\%$  or less. - Data on the screen-pairs made of mixtures of gadolinium oxysulphide and yttrium oxysulphide can, however, deviate by as much as  $\pm 10\%$  from their mean values. This is a consequence of their different contents of the two phosphors. - At higher radiation qualities the discrepancies become smaller:  $\pm 3\%$  or less for all of the screen pairs investigated.

The variations with radiation quality of the noise-equivalent absorption, shown in Figure 4, are very similar to those of the energy absorption (Holje, 1983 b). They are, however, somewhat smaller, which is due to the energy ratio,  $h\nu/E$ , which differs between the two quantities. This factor, when normalized to 80 kV filtered with 20 mm aluminium, varies by less than  $\pm 20\%$  around unity for all of the screen pairs investigated. - In the yttrium oxysulphide screens, it is less than  $\pm 4\%$ , i.e. almost constant. - In all of the screen pairs, except for that made of yttrium oxysulphide, this energy ratio increases with increasing tube potential and filter thickness. The energy absorption, on the other hand, decreases

when x-ray tube potential or filter thickness are increased (Holje, 1983 b). When these two quantities, therefore, are multiplied to yield the noise-equivalent absorption, less variations with radiation quality will appear.

The physical background of the variations in noise-equivalent absorption shown in Figure 3 is to be found in the energy absorption characteristics of the intensifying screens. The detailed analysis of the energy absorption characteristics made by Holje (1983 b) is, therefore, applicable to the characteristics of the noise-equivalent absorption also.

The importance of specifying radiation quality when comparing noise-equivalent absorption in screens made of different phosphors is evident from their different variations with radiation quality, as shown in Figure 3. Screen pairs, with equal noise-equivalent absorption at one radiation quality can differ quite drastically, when exposed to another radiation quality. Although equal at one radiation quality, a difference amounting to 2.5 at the extreme can be found at another radiation quality between the noise-equivalent absorption in two screens made of yttrium oxysulphide and gadolinium oxysulphide.

#### 3.4 The noise-equivalent number of absorption events in the screen-film systems at 80 kV filtered with 20 mm aluminium.

Table 3, column 1, presents the noise-equivalent number of absorption events,  $N_q$ , in the screen film systems, as determined according to Equation 5. The inverse of these numbers will be applied in the following for predictions of the quantum mottle in the screen-film system. To evaluate the accuracy of such predictions, an examination will be made of the correlation between these numbers of noise-equivalent absorption events (the quantum numbers), and those evaluated according to Equation 6 from measured radiographic mottle, the screen numbers.

Noise-equivalent number of absorption events evaluated from measured noise properties, the screen numbers. The radiographic mottle of the screen-film systems has been evaluated by Wiener spectral analysis (Holje and Doi, 1982). It was found that there are good reasons to believe that the Wiener spectral values at low spatial frequencies are good indicators

TABLE 3

Physical properties of screen-film systems at 80 kV and 20 mm Al

| Intensifying<br>screens | $\frac{N_q}{\text{mm}^{-2} \times 10^4}$ | $\frac{WS \text{ scr.mottle}}{\text{mm}^2 \times 10^{-4}}$ | $\frac{N_{WS}(D_N=1.0)}{\text{mm}^{-2} \times 10^4}$ | Rel.sens.at<br>equal noise |
|-------------------------|------------------------------------------|------------------------------------------------------------|------------------------------------------------------|----------------------------|
| M.R. 50                 | 10.76                                    | 1.23                                                       | 7.52                                                 | 2.06                       |
| M.R. 200                | 5.01                                     | 1.96                                                       | 4.71                                                 | 2.53                       |
| M.R. 400                | 2.20                                     | 4.06                                                       | 2.27                                                 | 2.29                       |
| M.R. 600                | 2.17                                     | 3.66                                                       | 2.52                                                 | 3.53                       |
| Rare Earth              | 2.41                                     | 2.66                                                       | 3.47                                                 | 3.12                       |
| Titan 923               | 1.82                                     | 3.95                                                       | 2.34                                                 | 2.35                       |
| Cronex Quanta II        | 2.38                                     | 3.51                                                       | 2.63                                                 | 2.71                       |
| Type 4360               | 3.19                                     | 3.89                                                       | 2.37                                                 | 2.24                       |
| Type 6359               | 3.03                                     | 3.81                                                       | 2.42                                                 | 2.94                       |
| X-Omatic Regular        | 5.99                                     | 1.57                                                       | 5.89                                                 | 2.88                       |
| Cronex Par Speed        | 4.58                                     | 2.27                                                       | 4.07                                                 | 1.00                       |
| Rubin Super             | 24.28                                    | 0.98                                                       | 9.44                                                 | 1.18                       |
| Grenex G-4              | 4.08                                     | 1.63                                                       | 3.82                                                 | 2.41                       |
| Grenex G-8              | 2.32                                     | 2.27                                                       | 2.74                                                 | 3.00                       |
| Lanex Fine              | 5.26                                     | 1.44                                                       | 4.32                                                 | 2.06                       |
| Lanex Regular           | 2.32                                     | 2.04                                                       | 3.05                                                 | 3.53                       |
| Trimax Alpha 4          | 3.11                                     | 1.78                                                       | 3.49                                                 | 1.88                       |
| Trimax Alpha 8          | 2.42                                     | 2.24                                                       | 2.78                                                 | 3.06                       |
| Rarex BG Detail         | 4.59                                     | 1.16                                                       | 5.37                                                 | 2.06                       |
| Rarex BG Mid Sp.        | 3.60                                     | 1.92                                                       | 3.24                                                 | 3.06                       |
| Rarex BG High Sp.       | 2.51                                     | 1.82                                                       | 3.42                                                 | 3.71                       |
| Rarex B Mid Sp.         | 1.83                                     | 3.56                                                       | 2.59                                                 | 2.12                       |

of the noise characteristics of screen-film systems. One of the reasons for this is that these values are not influenced by the resolution properties of the systems. The other was based on the result of an observer performance experiment, which showed that these Wiener spectral values appear to be closely related to detail visibility of low contrast images.

Table 3, column 2, presents the measured Wiener spectral values at low spatial frequencies for the screen-film systems. Since these Wiener spectral values are those of the radiographic mottle subtracted with that of the film mottle, they represent the total screen mottle: quantum mottle and screen structure mottle (the direct and/or indirect imaging of the fluorescent crystals). No attempts have been made here to isolate the values of the quantum mottle. Such an extensive investigation was considered to be unjustified, especially as the structure mottle has been regarded as being negligible compared to the quantum mottle (Rossman, 1963; Doi, 1969). The noise-equivalent number of absorption events determined from these Wiener spectral values, the screen numbers, may therefore be influenced not only by the quantum mottle but also by the screen structure mottle. They will be denoted as  $N_{WS}$  in the following text. By expressing the structure mottle as the reciprocal of a structure number,  $N_{Str.}$ , the Wiener spectral values at low spatial frequencies, of the total screen mottle can be expressed as:

$$\Phi_{\text{screen mottle}} = \Phi_{\text{q. mottle}} + \Phi_{\text{str. mottle}} \sim \frac{1}{N_{WS}} = \frac{1}{N_q} + \frac{1}{N_{str}} \geq \frac{1}{N_q} \quad (11)$$

Equation 11 shows that equality can be expected between the quantum number and screen number only when the structure number is very much higher than the quantum mottle. With this exception, the quantum number will always adopt values which are higher than the screen number.

The screen numbers,  $N_{WS}$ , for the screen-film systems are presented in column 3 of Table 3. They have been evaluated according to Equation 6 by inserting the gradient of the film. This is 2.87 for the blue sensitive film, and 2.30 for the green sensitive film (Holje and Doi, 1982). Corrections have also been made to compensate for the fact that the film density, used in the analysis of radiographic mottle, was lower than that employed



for the determinations of the quantum number.

The correlation between quantum numbers and screen numbers. In Figure 5, the screen numbers,  $N_{WS}$ , are plotted versus the quantum numbers,  $N_q$ , for the screen-film systems. The diagonal line indicates equality between the two values. In spite of the predictions made in connection with Equation 11, more than half of the screen-film systems have adopted quantum numbers which are lower than the screen numbers. These low values of the quantum numbers are only partly explained by the underestimations of, at the most, 10 % of the noise-equivalent absorptions mentioned in Chapter 3.2.

In the calculations of the quantum numbers, doubts were expressed about how to treat the absorption events of inherently produced K x-ray energy. It was found to be most relevant to treat them as separate energy absorption events in most of the screens. In the yttrium oxysulphide screens, however, determinations were also performed for the case where K x-ray absorption is treated as a part of the primary event. The quantum number, determined according to this latter model, is found in parenthesis in Figure 5. As expected, this value is lower than that determined according to the model where K x-ray absorption is treated as a separate event. It is obvious from Figure 5 that the "separate-event"-value of the quantum number agrees better with the screen number. Judging from this, one might conclude that the better of these two models is the one treating K x-ray absorption as a separate event.

A change in the absolute sensitivity of the films employed in the two determinations of the noise-equivalent number of absorption events is one plausible explanation for the finding that the quantum numbers have adopted lower values than the screen numbers. If the sensitivity of the films used for the calculation of the quantum numbers has been higher than that of the films used in the Wiener spectral measurements, data like those presented in Figure 5 would have been obtained. Being aware of these difficulties, the aim of this investigation has not been to seek a relationship in absolute terms, but rather in relative terms, between the predictions and measurements of quantum mottle. An indicator of quantum mottle, which is correct in relative terms, is as useful as the one which

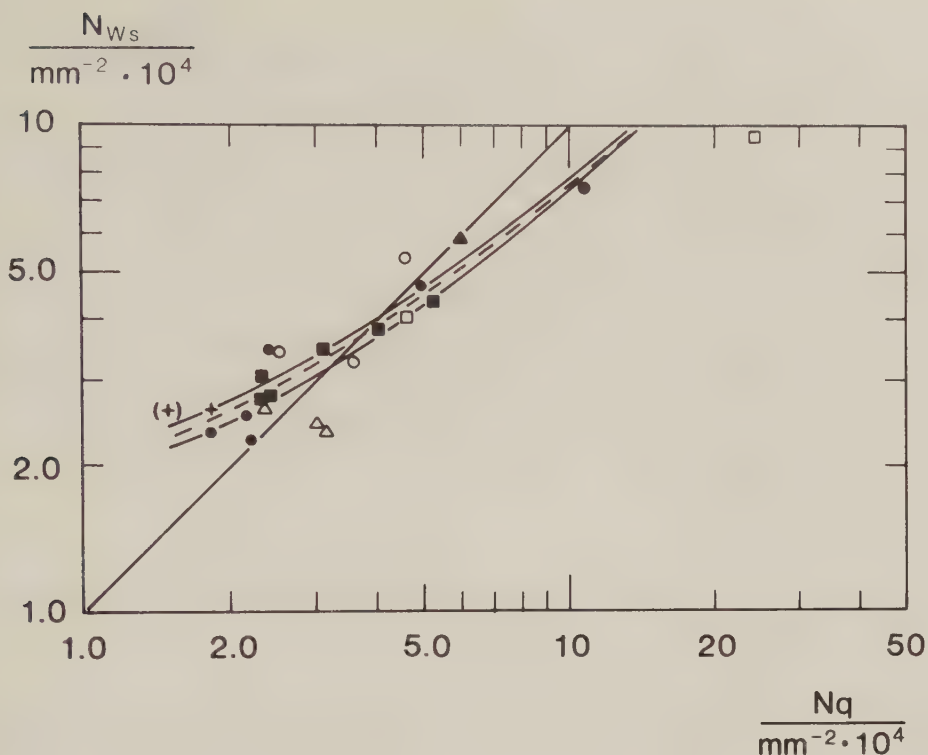


Figure 5. Noise equivalent number of absorption events at 80 kV filtered with 20 mm aluminium. Screen numbers,  $N_{ws}$ , versus quantum numbers,  $N_q$ , for the screen-film systems. + —  $Y_2O_2S$ -screens,  $\Delta$  —  $BaFCl$ -screens,  $\blacktriangle$  —  $BaSO_4/SrSO_4$ -screens,  $\bullet$  —  $LaOBr$ -screens,  $\blacksquare$  —  $Gd_2O_2S$ -screens,  $\circ$  —  $Gd_2O_2S/Y_2O_2S$ -screens,  $\square$  —  $CaWO_4$ -screens. The line indicates equality between the two numbers. The curves are fitted by linear regression analysis to the values for the screen-film systems.

is correct in absolute terms, when the aim is as here, to clarify differences in noise characteristics of different screen-film systems. If and when a reliable relative correlation is found, it is realistic to attempt to find the connection in absolute terms between predicted and measure quantum mottle. It will be seen that there are good reasons to believe that the relationship in Figure 5 shows a realistic relative correlation between the quantum numbers and the screen numbers. At present, however, no solid proof is put forth to explain the low values of the quantum numbers.

Linear regression analysis of the data points has been performed, and the resulting curves are shown in Figure 5. The upper curve represents the

the "green sensitive" systems, the lower curve the "blue sensitive" systems, and the middle curve represents all of the systems, regardless of the film type used. (The calcium tungstate system, Rubin Super, has been omitted in this analysis.) The fact that the two curves, representing systems employing blue and green sensitive films, do not coincide, indicates that the relative sensitivity between these films has not been the same in the determinations of the quantum numbers and the screen numbers.

The linear gradients of the three curves are between 0.62 and 0.63, i.e. the screen numbers do not increase in accordance with the quantum numbers. This indicates that the structure mottle is not negligible. Equation 11 can thus be rewritten as:

$$\Delta N_{WS} \leq \Delta N_q \quad (12)$$

where equality exists only when the structure mottle is negligible, i.e. when the structure number approaches infinity.

The influence of structure mottle on the correlation between quantum numbers and screen numbers. Figure 6 presents the same information as Figure 5, except that the quantum numbers have been multiplied by a factor of 1.35. This is to compensate for the underestimated noise-equivalent absorption and for the plausible higher sensitivity of the films used in the determinations of the quantum numbers, compared to those used in the determinations of the screen numbers. The diagonal line indicates equality between the quantum numbers and the screen numbers. This applies to screens with a structure mottle which is negligible compared to the quantum mottle. This is indicated by the structure number infinity. The three solid curves in Figure 6 illustrate expected correlations between the quantum numbers and screen numbers when the structure mottle is non-negligible. The values chosen for the structure numbers are  $1 \times 10^5$ ,  $2 \times 10^5$  and  $4 \times 10^5 \text{ mm}^{-2}$ . These values are equal to, and up to ten times larger, than the quantum numbers determined for the different screen-film systems. - Expressed in terms of radiographic mottle, this is equivalent to screen structure mottles which are equal to or down to one-tenth of the quantum mottle of the screen-film systems.

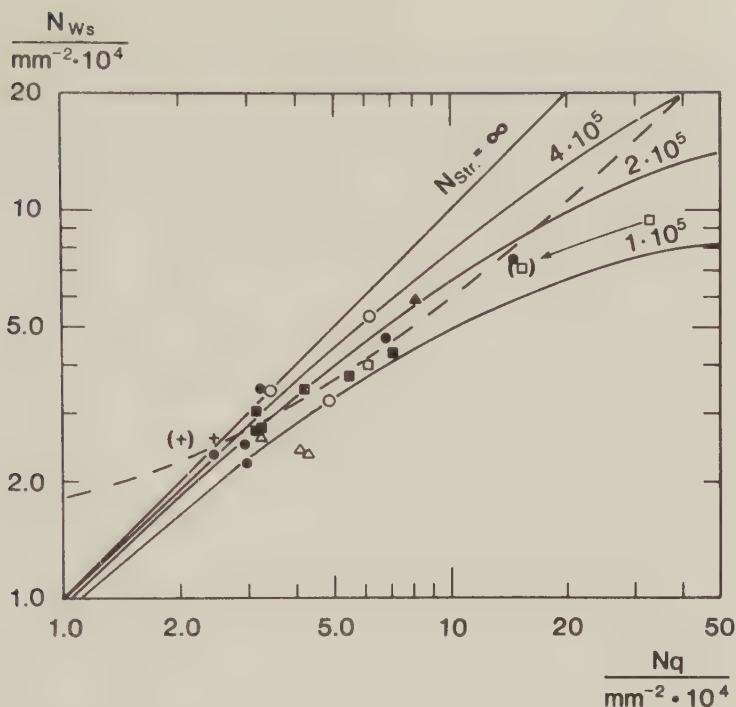


Figure 6. Noise-eq. number of abs. events at 80 kV and 20 mm Al. Screen numbers,  $N_{ws}$ , versus quantum numbers,  $N_q$ . + -  $Y_2O_3$ -screens,  $\Delta$  - BaFCL-screens,  $\blacktriangle$  -  $BaSO_4/SrSO_4$ -screens,  $\bullet$  - LaOBr-screens,  $\blacksquare$  -  $Gd_2O_3$ -screens,  $\circ$  -  $Gd_2O_3/Y_2O_3$ -screens,  $\square$  -  $CaWO_4$ -screens, (+) -  $Y_2O_3$ -screens (K x-ray abs. add. to prim. event). ---curve fitted by linear regr.anal. to the values for the screen-film systems. — predicted correlations between  $N_{ws}$  and  $N_q$  at various magnitudes of the structure number,  $N_{str}$ .

It is obvious that the curve representing the structure number  $2 \times 10^5 \text{ mm}^{-2}$  agrees very well with the dotted curve, which is fitted to the data points by regression analysis. Also the data point of the calcium tungstate system, Rubin Super, fits into the model when the existence of structure mottle is assumed. Due to the lack of a solid correlation in absolute terms between the quantum numbers and screen numbers presented in Figure 6, the structure number  $2 \times 10^5 \text{ mm}^{-2}$  can not seriously be regarded as an absolute value. The agreement between this curve and the average of the data points merely indicates that the correlation found between the two numbers is due to the existence of structure mottle. The crude estimation can also be made, that the structure mottle may amount to roughly 10 % of the total screen mottle in systems with high quantum mottle, i.e. those with low quantum numbers. This result is very close



to earlier findings (Doi, 1969). The structure mottle in systems with low quantum mottle can amount to about 50 % of the total screen mottle. In the case of the Rubin Super system, the structure mottle is estimated to be about twice as high as the quantum mottle, or  $2/3$  of the total screen mottle. The phosphor layers of these screens contain a dye to reduce light scatter, for the purpose of improving the resolution capacity. This also reduces their light-yield, which has the consequence that high absorbed energy, and thus a large number of absorption events, are needed in this system for the production of a certain film density. It is questionable if it is worthwhile to reduce the quantum mottle to such an extent that the structure mottle dominates. An increase, in this case, of the quantum mottle by a factor of two will decrease the patient dose to one-half, while the total screen mottle will increase by only 33 %. This can easily be accomplished by using a film with twice the sensitivity. The estimated resulting shift of the data point of the Rubin Syper system is shown in Figure 6, and an interesting finding is that the "new" Rubin Super system almost coincides with the lanthanum oxybromide system, M.R. 50. This is very good evidence that the screen number and quantum number determined on the Rybin Super system are quite realistic. Its somewhat odd fitting to the majority of the data points is determined solely by the fact that its structure mottle dominates the radiographic mottle.

Two-thirds of the data points in Figure 6 agree within  $\pm 10$  % with the fitted average, indicated by the dotted curve. Assuming that this fluctuation is due to the inaccuracy of the measurements and calculations performed to derive the screen numbers and quantum numbers, this agreement is satisfactory. - The Wiener spectra measurements, which form the basis for determination of the screen numbers, have been confirmed to be reproducible within 10 per cent (Doi et al., 1982). The determinations of the energy absorbed, which are the basis of the calculations of the quantum numbers, have been estimated to be accurate within less than  $\pm 10\%$  (Holje, 1983 c). The spread of the data points around the average may, however, also depend on differences in the structure mottle in the various scrrren-film systems. There is no reason to believe that the structure mottle should be equal in all of the intensifying screens. - Technical processes of screen manufacturing might cause differences in structure



mottle between screens made by the different manufacturers. Differences in the chemical composition and binding material of the screens may be another reason for the differences in the structure mottle. Crystal size, screen thickness, reflecting material, dye etc., factors which may differ between high and low sensitive systems, are also plausible causes of differences in the resulting structure mottle. - There is one good reason on the other hand, that the structure mottle can not be expected to vary highly between different intensifying screens: Screens producing images with unusually high mottle can not be competitive for any longer period of time, and they will, therefore, disappear from the market.

Data on only two of the screen pairs investigated deviate to such an extent from the rest of the systems, that one dare to conclude, that their structure mottles are considerable. These are the two barium fluoro-chloride screens, manufactured by Philips, type 4360 and type 6359. Their structure numbers fall between  $5 \times 10^4$  and  $6 \times 10^4 \text{ mm}^{-2}$ . This is comparable to their quantum numbers, which are approximately  $4 \times 10^4 \text{ mm}^{-2}$ . These structure numbers are to be compared to those between  $1 \times 10^5 \text{ mm}^{-2}$  and infinity, which were derived for the other systems. The very good resolution properties of these two barium fluorochloride systems (Holje, 1983 g) support the visualization of their radiographic mottle. Images produced with these systems have a pronounced radiographic mottle, which is easily detected in visual comparisons.

The conclusion which can be drawn from this investigation is that the relative levels of quantum mottle of screen-film systems can be predicted with good accuracy from their energy absorption characteristics. The existence of structure mottle, however, implies risks for using only their energy absorption properties as indicators of the total radiographic mottle. The results achieved here indicate that further investigations are warranted, aiming at the correlation in absolute terms between predicted quantum mottle and measured radiographic mottle. If such investigations are to be successful, special attention must be paid to the quantification of structure mottle.

### 3.5 The influence of radiation quality on the quantum mottle.

In Equation 8 it was shown that the variation of the quantum mottle with radiation quality can be predicted from the variations in the mean energy deposition in the screens. Figure 7 presents the theoretically predicted quantum mottle - the mean energy deposition - in the screen-film systems, at various radiation qualities relative to that achieved at the radiation quality produced at 80 kV filtered with 20 mm aluminium. All screen-film systems with phosphors containing the same high Z-element are treated as one group, and their mean values are presented. At the lowest radiation qualities, data on individual screen-film systems differ from these mean values by  $\pm 1\%$  or less. At higher radiation qualities, this discrepancy is smaller.

According to Figure 7, the quantum mottle in the screen-film systems increases as the x-ray tube potential or the filtration of the the x-ray beam increases. This applies to all of the screen-film systems investigated, although the magnitude of the increase depends on the phosphor material. This is a direct consequence of the increase in mean energy deposition, which is determined by the energy absorption characteristics of the screens. A crucial point in this context is the energy at which K-shell absorption in the high atomic element of the phosphors occurs (Holje, 1983 b).

The quantum mottle in gadolinium oxysulphide systems is very little affected by the radiation qualities used here. This was also the case for their variation in attenuation (Holje, 1983 a), energy absorption (Holje, 1983 b), sensitivity (Holje, 1983 c) and noise-equivalent absorption (Section 3.3). It is quite evident that the gadolinium oxysulphide systems are outstanding as to the constancy of their physical properties when they are exposed to various radiation qualities.

The variation with radiation quality of the quantum mottle in yttrium-oxysulphide systems is comparatively large. This also applies to their variations in other physical properties (Holje, 1983 a,b,c,Sect.3.3). The quantum mottle in systems made of lanthanum oxybromide, barium fluoro-chloride, barium sulphate/strontium sulphate and calcium tungstate adopts an intermediate position regarding its variation with radiation quality.

$$\bar{E}_{x,y} / \bar{E}_{80,20}$$

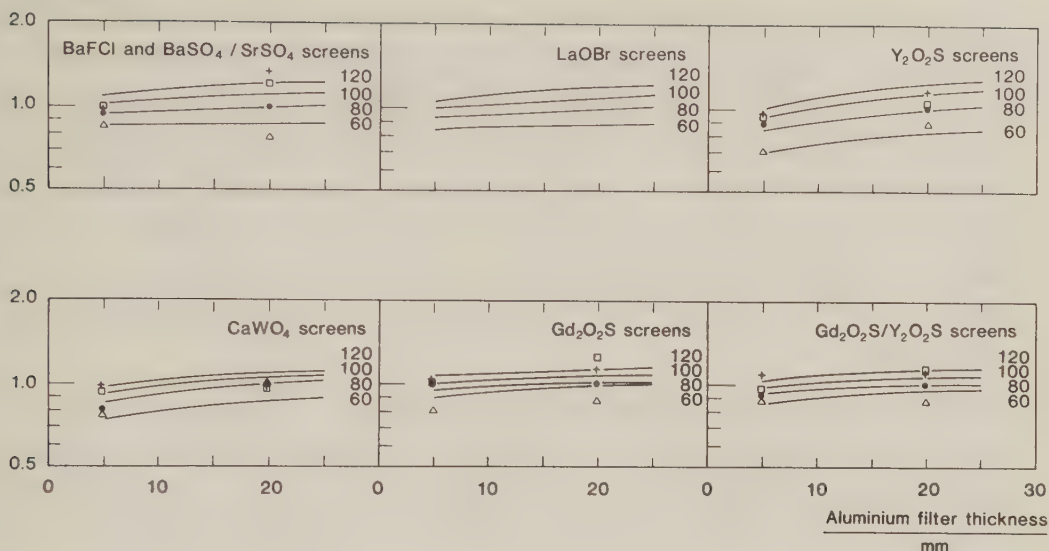


Figure 7. Predicted quantum mottle in the screen-film systems at various incident radiation distributions relative to that at 80 kV filtered with 20 mm aluminium,  $\bar{E}_{x,y} / \bar{E}_{80,20}$ . x denotes the x-ray tube potential and y the aluminium filter thickness.  $\Delta$  — measured screen mottle at 60 kV,  $\bullet$  — 80 kV,  $\square$  — 100 kV and + — 120 kV.

This is also the case for other physical properties of these screen-film systems (Holje, 1983 a,b,c, Sect.3.3).

The significance of the variations in quantum mottle in clinical examinations shown in Figure 7 has not been investigated. One would expect, however, that preference would be given to systems which do not have high fluctuations in their image quality in relation to the incident radiation quality. The use of gadolinium oxysulphide screens should, therefore, be more suitable for clinical work, since they do not introduce any high variations in quantum mottle depending on the radiological examination being performed.

The correlation between predicted and measured quantum mottle at various radiation qualities. The radiographic mottle has been experimentally evaluated in five selected systems of BaSO<sub>4</sub>/SrSO<sub>4</sub>, Y<sub>2</sub>O<sub>2</sub>S, CaWO<sub>4</sub>, Gd<sub>2</sub>O<sub>2</sub>S and Gd<sub>2</sub>O<sub>2</sub>S/Y<sub>2</sub>O<sub>2</sub>S. The Wiener spectra of the radiographic mottle in these systems were measured (Doi et al., 1982) at the radiation qualities produced at 60, 80, 100 and 120 kV filtered with 5 and 20 mm aluminium. The Wiener

spectral values of the screen mottle, relative to those determined at 80 kV filtered with 20 mm aluminium, are indicated by the data-points in Figure 7. No attempts have been made to separate the quantum mottle from structure mottle in these evaluations. If there should be any significant contribution of structure mottle to the total screen mottle, the experimentally determined variations should be less than those predicted theoretically for the quantum mottle alone. The limited precision of the measurements is, however, also limiting for the investigations of such fine details.

The experimentally determined variations in screen mottle agree fairly well with the predictions of the quantum mottle variations calculated from the energy absorption characteristics of the screens. Seventy-five per cent of the measured data agree within  $\pm 10\%$  with the predicted values. The remaining 25 % agree within about  $\pm 15\%$ . This inaccuracy is about what can be expected, since no repeated measurements have been performed.

### 3.6 Sensitivity, noise-equivalent absorption and quantum mottle.

Due to their high noise-equivalent absorption, the new screens should be expected to produce images with less quantum mottle than those produced in calcium tungstate systems. The quantum mottle, however, is also influenced by the light-yield of the screens and the sensitivity of the film. Systems with screens with high light-yield and/or films with high sensitivity provide little absorbed energy, few absorption events, and, thus high quantum mottle. In the light of their favourable absorption characteristics, it may seem that problems with high quantum mottle should never arise in the new screen-film systems. These came, however, from the desire to utilize the high conversion efficiency of the new phosphors. The sensitivity of the screen-film systems could thereby be increased, which, in turn, provides reduced patient doses.

In spite of their high noise-equivalent absorption, it is evident from Table 2 that the noise equivalent number of absorption events in only five new screen-film systems exceed that in the medium sensitive calcium tungstate system. The quantum mottle can consequently in only these five systems be expected to be lower than that in the Cronex Par Speed system.

A comparison of the quantum mottle in various screen-film systems, however, is significant only when this is correlated to their sensitivities. The relationship between sensitivity, noise equivalent absorption and quantum mottle can be expressed from Equation 9 as:

$$\frac{1}{N_q} = \frac{1}{B_N} \cdot S \cdot \overline{h\nu} \quad (13)$$

where

$B_N$  is the noise-equivalent absorption,

$1/N_q$  the inverse quantum number is employed as a measure of the quantum mottle

$S = \left( \int_{h\nu \text{ min}}^{h\nu \text{ max}} \frac{d\Psi}{d h\nu} d h\nu \right)^{-1}$  is the sensitivity of the screen-film system, (Holje 1983 c), and

$\overline{h\nu}$  is the mean energy of the incident photon fluence.

Equation 13 indicates that high quantum mottle is related to low noise-equivalent absorption, high sensitivity and high mean energy of the incident photon distribution.

The light-yield of the screens has been used in another publication as an indicator of the expected quantum mottle (Holje, 1983 c). The relationship between these two quantities is obtained from Equation 5 as:

$$\frac{1}{N_q} = \overline{E} \cdot \frac{1}{C} = \overline{E} \cdot LY \quad (14)$$

where

$\overline{E}$  is the mean energy deposition and

$LY = 1/C$  is the light-yield defined as the inverse of the energy absorbed per unit area of the screens (Holje, 1983 c).



For a first-order approximation, therefore, data on relative light-yield can be utilized in predictions of the relationship between the quantum mottle in different screen-film systems. The better the agreement between the magnitude of the mean energy deposition in two such systems, the more accurate will the predictions become. The mean energy deposition in all of the new screen-film systems is, however, lower than that in calcium tungstate systems. Predictions of quantum mottle in the new screen-film systems, relative to that in calcium tungstate systems, by means of light-yields will, therefore, not give full credit to the new systems.

Figure 8 provides a comprehensive presentation of the physical properties of sensitivity, noise-equivalent absorption and quantum mottle in the screen-film systems. There is a general tendency in Figure 8, that high sensitivity of the screen-film systems results in high quantum mottle. The increase in sensitivity attained with the new systems compared to that of the calcium tungstate systems is, however, higher than the increase in their quantum mottle. This is a consequence of their higher noise-equivalent absorption.

The most sensitive system, the lanthanum oxybromide system, M.R. 600, has more than seven times higher sensitivity than the Cronex Par Speed system of calcium tungstate. The increase in quantum mottle is, however, only slightly more than a factor of two. This discrepancy is due to the 3.5 times higher noise-equivalent absorption in the M.R. 600 screens.

The physical properties of the two systems Cronex Par Speed and X-Omatic Regular give interesting comparisons. The sensitivity of the X-Omatic Regular system is more than twice as high as that of the Par Speed system. Its noise-equivalent absorption is, however, almost three times as high. This has the result that the quantum mottle in the X-Omatic Regular system is about 25 % lower than that in the Par Speed system.

The two high sensitive lanthanum oxybromide systems, Titan 923, the upper filled circle in Figure 8, and Rare Earth, the lower filled circle, enable another interesting comparison. These two systems have equal sensitivity, but the quantum mottle in the Rare Earth system is 25 % lower. Different weightings between energy absorption and light-yield have been utilized in these two systems to attain the same sensitivity (Holje, 1983 c). This

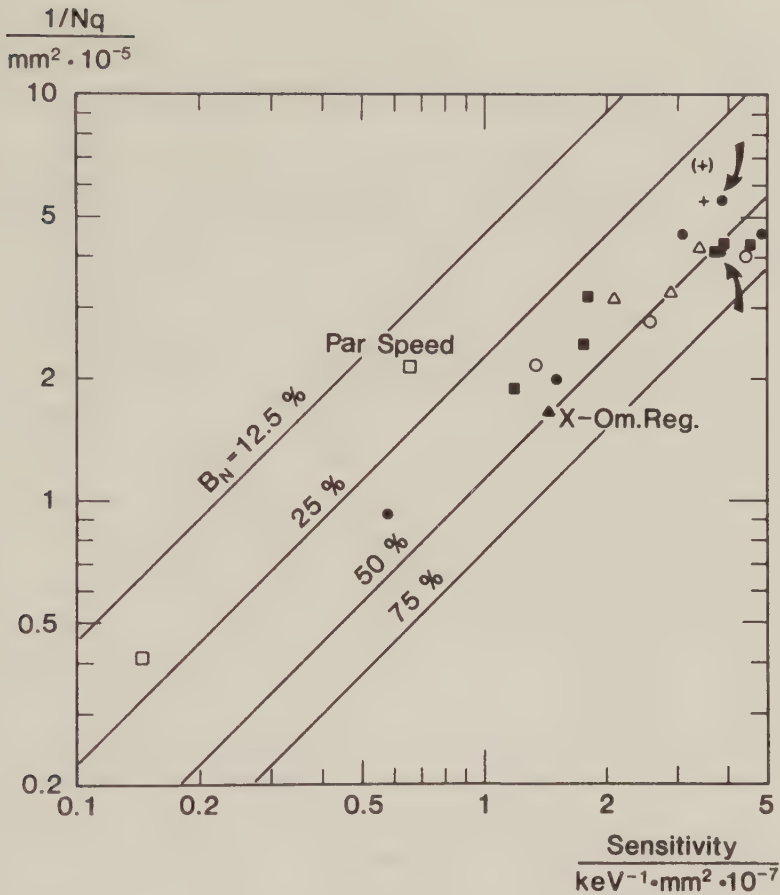


Figure 8. Sensitivity, noise-equivalent absorption and quantum mottle.  $1/Nq$ , the inverse quantum number is an indicator of quantum mottle. The diagonal lines indicate noise-equivalent absorption,  $B_N$ .  
 + —  $Y_2O_2S$ -screens,  $\Delta$  —  $BFC1$ -screens,  $\blacktriangle$  —  $BaSO_4/SrSO_4$ -screens,  
 $\bullet$  —  $LaOBr$ -screens,  $\blacksquare$  —  $Gd_2O_2S$ -screens,  $\circ$  —  $Gd_2O_2S/Y_2O_2S$ -screens,  
 $\square$  —  $CaWO_4$ -screens, (+) —  $Y_2O_2S$ -screens (K x-ray abs.add.to prim.event).

weighting is of vital importance for the resulting quantum mottle. Systems with high energy absorption and low light-yield are predicted to provide low quantum mottle. Since the light-yield of the Rare Earth system is lower than that of the Titan 923 system by 25 %, the observed difference in quantum mottle between these two systems corresponds exactly to their different light-yield.

The noise-equivalent absorption,  $B_N$ , which is indicated by diagonal lines in Figure 8, is a parameter of specific interest, since it expresses iso-

lated property of the intensifying screens. The sensitivity, as well as the quantum mottle, are properties of the screens in combination with specific film types. If the intensifying screens are combined with films of other sensitivities than those of the ones used, the data-points in Figure 8 will shift parallel to the diagonal lines. It is possible, through proper choices of films, to let all of the screen-film systems adopt the same quantum mottle as that in the Cronex Par Speed calcium tungstate system. The sensitivities of the screen-film systems at such "equal noise conditions", relative to that of the Cronex Par Speed system are shown in column 4 of Table 3. The most sensitive system is the high-sensitive gadolinium oxysulphide/yttrium oxysulphide system, which under this condition provides a sensitivity gain by a factor of 3.7. This is thus the highest sensitivity gain which can be attained with the new screen-film systems, provided that the quantum mottle is not allowed to increase.

Due to their higher noise equivalent absorption, all new screen-film systems will attain higher sensitivity than the Par Speed calcium tungstate system under equal noise conditions. The sensitivity gains, which vary between 1.9 and 3.7, are remarkable. Furthermore, as many as eight of the 20 new screen-film systems investigated have equal or better resolution capacity than the Cronex Par Speed system (Holje, 1983 g). It is obvious therefore, that it is possible to reduce the patient dose by at least a factor of two by using new screen-film systems with the same or better image quality than that of a medium sensitive calcium tungstate system. Similar findings are reported in an investigation where the noise properties were evaluated by means of Wiener spectral analysis (Holje and Doi, 1982).

## REFERENCES

Barnes G.T., 1976.

The dependence of radiographic mottle on beam quality.

American Journal of Roentgenology 127:818-824.

Buchanan R.A., Finkelstein S.I. and Wickersheim K.A., 1972.

X-Ray exposure reduction using rare-earth intensifying screens.

Radiology 105:185-190.

Cleare H.M., Splettstosser H.R. and Seemann H.E., 1962.

An experimental study of the mottle produced by X-ray intensifying screens.

The American Journal of Roentgenology, Radium Therapy and Nuclear Medicine LXXXVIII(1):168-174.

Danily J.C. and Shaw R., 1974.

Image Science.

Academic Press Inc., London.

Doerner E.C., 1962.

Wiener-spectrum analysis of radiographic green larity.

Journal of the Optical Society of America 52(6):669-672.

Doi K., 1969.

Wiener spectrum analysis of quantum statistical fluctuation and other noise sources in radiography.

In Television in Diagnostic Radiology, eds. Mosely R.D. and Rust J.H., Aesculapius Publ. Co. 313-333.

Doi K. and Imhof H., 1977.

Noise reduction by radiographic magnification.

Radiology 122:479-482.

Doi K., Holje G., Loo L.N., Chan H.P., Sandrik J.H., Jennings R.J. and Wagner R.F., 1982.

MTF's and Wiener spectra of radiographic screen-film systems. Part 1. Interlaboratory comparison of measurements.

U.S. Department of Health and Human Services Publication FDA 82-8187, Bureau of Radiological Health, Rockville, Maryland 20857.

Holje G., 1983 a.

Photon attenuation by intensifying screens used in diagnostic radiology. CODEN Report LUNFD6 (NFRA-3033) / LUMEDW (MERI-3033), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 b.

Energy absorption in radiographic intensifying screens. CODEN Report LUNFD6 (NFRA-3034) / LUMEDW (MERI-3034), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 c.

Sensitivity characteristics of radiographic screen-film systems. CODEN Report LUNFD6 (NFRA-3035) / LUMEDW (MERI-3035), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 e.

Energy absorption of fluorescent K X-rays produced in the phosphor layers of radiographic intensifying screens.

CODEN Report LUNFD6 (NFRA-3037) / LUMEDW (MERI-3037), Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., 1983 f.

Coefficients for converting X-ray exposure to photon fluence and energy fluence.

CODEN Report LUNFD6 (NFRA-3038) / LUMEDW (MERI-3038), Dept. of Radiation Physics, Lund University, Lund, Sweden.



Holje G., 1983 g.

Physical properties of radiographic screen-film systems. Doctoral thesis.  
Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., Svahn G., Hårdstedt C., Ramnhagen A., Öberg A. and Forsberg H.,  
1977.

Intensifying screens for X-ray cassettes, performance, usability, etc.  
(in Swedish, English summary).

The Swedish Institute for the Planning and Rationalization of Health and  
Social Welfare Services Publication S 67.

Holje G. and Westrup C., 1978.

Absorption and noise characteristics of screen-film systems.

Paper presented at the XXXV Annual Meeting of the

Holje G. and Doi K., 1982.

MTF's and Wiener spectra of radiographic screen-film systems. Part 2.  
Sensitivity, sensitometry, resolution and noise characteristics of new  
screen-film systems.

U.S. Department of Health and Human Services Publication FDA 82-8187,  
Bureau of Radiological Health, Rockville, Maryland 20857.

Jures K. and Rudinger G., 1938.

On problems of gramines of radiographs prepared with intensifying screens.  
Fortscritte a. d. Geb. d. Röntgenstrahlen 57:53-56.

Rao G.U.V. and Fatouros P.P., 1979.

Quantum fluctuations in radiographic screen-film systems.  
Medical Physics 6(2):118-122.

Rose A., 1953.

Quantum and noise limitations of the visual process.  
J. of the Opt. Soc. of Am. 43:715-716.

Rossmann K., 1962 a.

Modulation transfer function of radiographic systems using fluorescent screens.

Journal of the Optical Society of America 52(7):774-777.

Rossmann K., 1962 b.

Recording of quantum fluctuations in radiographs.

Journal of the Optical Society of America 52(10):1162-1164.

Rossmann K., 1963.

Spatial fluctuations of X-ray quanta and the recording of radiographic mottle.

American Journal of Roentgenology, Radium Therapy and Nuclear Medicine XC(4):863-869.

Rossmann K., 1968.

Detail visibility in the presence of quantum fluctuations.

In Fundamental problems in scanning, eds. Gottschalk A. and Beck R.N., Charles C. Thomas Publisher, Springfield, Illinois, 326-335.

Sandrik J.N. and Wagner R.F., 1982.

Absolute measures of physical image quality: Measurement and application to radiographic magnification.

Medical Physics 9(4):540-549.

Stevens A.L.N. and Pingault F., 1975.

BaFCl:Eu<sup>2+</sup>, A new phosphor for X-ray intensifying screens.

Philips Res. Reports 30:277-290.

Swank R.K., 1973.

Absorption and noise in X-ray phosphors.

Journal of Applied Physics 44(9):4199-4203.

Wagner R.F., 1977 a.

Text Fourier digital quantum mottle analysis with application to rare-

earth intensifying screen systems.

Medical Physics 4(2):157-162.

Wagner R.F., 1977 b.

Noise equivalent parameters in general medical radiography: The present picture and future pictures.

Photographic Science and Engineering 21(5):252-262.

Wagner R.F. and Weaver K.E., 1975.

Noise measurements on rare-earth intensifying systems.

SPIE Vol. 56, Medical X-ray photo-optical systems evaluation, 198-207.

Wagner R.F. and Weaver K.E., 1977.

Prospects for X-ray exposure reduction using rare-earth intensifying screens.

Radiology 118:183-188.

Vyborny C.J., Loo L.N. and Doi K., 1982.

The energy-dependent behaviour of noise Wiener spectra in their low-frequency limits: Comparison with simple theory.

Radiology 144(3):619-622.









Dokumentutgivare  
Inst för radiofysik  
Handläggare  
Författare  
Gunnela Holje

Dokumentnamn  
CODEN Report  
Utgivningsdatum  
April 1983

Dokumentbeteckning  
3037  
Ärendebeteckning

Dokumenttitel och undertitel

ENERGY ABSORPTION OF FLUORESCENT K X-RAYS PRODUCED IN THE PHOSPHOR  
LAYERS OF RADIOGRAPHIC INTENSIFYING SCREENS

Referat (sammmandreg)

The attenuation and energy absorption of the K X-rays, which are emitted from the highest Z-element of the phosphor, have been determined in twenty-two intensifying screens with seven different phosphor compositions. A simple relationship is established between the attenuation of internally produced K X-rays and the attenuation by the screens of perpendicularly incident photons of equivalent energy. To show the correct proportions of the absorption of K X-ray energy in the screens, it will be related to the total energy absorption of incident photons. This ratio is expected to be applicable for predicting the influence of absorbed K X-rays on the quantum mottle and the resolution properties of the screen-film systems.

Referat skrivet av

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Indextermer (ange källa)

Omfång

Övriga bibliografiska uppgifter

Språk

Sekretessuppgifter

ISSN

ISSN

Dokumentet kan erhållas från

Mottagerens uppgifter

Inst för radiofysik vid Lunds universitet  
Lasarettet  
S-221 85 LUND

Pris

SIS-  
DB 1

DOKUMENTTABLAD enligt SIS 62 10 12

Blankett LU 11:25 1976-07



ENERGY ABSORPTION OF  
FLUORESCENT K X-RAYS PRODUCED IN  
THE PHOSPHOR LAYERS OF RADIOGRAPHIC  
INTENSIFYING SCREENS

Gunnila Holje

Lund 1983





| <u>CONTENTS.</u>                                                                                                     | Page |
|----------------------------------------------------------------------------------------------------------------------|------|
| 1. INTRODUCTION.....                                                                                                 | 1    |
| 2. THEORETICAL DETERMINATIONS.....                                                                                   | 2    |
| 2.1 Model used for determinations of the attenuation of<br>fluorescent K x-rays produced in the intensifying screens | 2    |
| 2.2 Determinations of the energy absorption of fluorescent<br>K x-rays produced in the screens                       | 7    |
| 2.3 Contribution of absorbed K x-ray energy to the total<br>energy absorbed by the screens                           | 9    |
| 3. RESULTS AND DISCUSSION.....                                                                                       | 11   |
| 3.1 Attenuation of internally produced K x-rays.                                                                     | 11   |
| 3.2 Energy absorption of K x-rays.                                                                                   | 14   |
| 3.3 Contribution of absorbed K x-ray energy to the total<br>energy absorbed by the screens.                          | 16   |
| REFERENCES.....                                                                                                      | 18   |



## 1. INTRODUCTION

The high sensitivity achieved with the new screen-film systems is partly a result of their high absorption of incident energy fluences to which they are exposed in different clinical radiological examinations. It has been shown that this high energy absorption is due to the favourable matchings, which exist between the energy absorption of monoenergetic photons in the new phosphor screens and the distributions of incident photon fluences (Buchanan et al., 1973, Holje, 1983 b). The high occurrence of K-shell interactions, with the consecutive higher reabsorption of emitted K x-ray energy, which promote the sensitivity of the new screen-film systems, has, however, been shown to be a disadvantage for their resolution properties (Karlsson et al., 1977; Arnold and Bjärngard, 1979). In spite of this unfavourable condition, the measured resolutions of the new screen-film systems are definitely superior to those of conventional calcium tungstate systems with comparable sensitivity (Holje et al., 1977; Holje and Doi, 1982; Holje, 1983 g). Reabsorption of K x-rays seems to be advantageous not only for the sensitivity of screen-film systems, but also for their quantum mottle. An abrupt decrease of the quantum mottle has been shown at photon energies exceeding that of the K-absorption edge of the high Z-element of the phosphor (Vyborny et al., 1982). Aiming at a better understanding of its influence on the sensitivity, noise and resolution properties of screen-film systems, a quantification of the re-absorbed K x-ray energy will be made in this investigation.

Shuping and Judy (1977) and Vyborny et al. (1978) have calculated the attenuation and energy absorption of the K x-rays produced in radiographic screens. It was shown that these contribute by more than 50 % of the energy absorbed in thick screens at incident photon energies just above the K-absorption edge. When the incident photons have a broad spectral distribution, as is the case in diagnostic radiology, the contribution from K x-rays is lower. It can, however, amount to as much as 25 % of the total energy absorbed in thick screens (Holje, 1983 b).

The attenuation and energy absorption of the K x-rays, which are emitted from the highest Z-element of the phosphor, will be determined in this investigation. A simple relationship will be established between the attenuation of internally produced K x-rays in the screens and the attenuation by the screens of perpendicularly incident photons of equivalent energy. To give correct proportions to the absorption of K x-ray energy in the screens, it will be related to the total energy absorption of incident photons. This ratio is expected to be applicable to predictions of the influence of reabsorbed K x-rays on the quantum mottle and the resolution properties of the screen-film systems.

## 2. THEORETICAL DETERMINATIONS

### 2.1 Model used for determinations of the attenuation of fluorescent K x-rays produced in the intensifying screens.

The intensifying screens incorporated in this study are listed in Table 1. The table also shows the chemical composition of their phosphor layers and the energy of the K-absorption edge(s) of their high Z-element(s). In most radiological examinations, these screens are exposed to broad photon distributions, which cover energy intervals between 10 keV and 150 keV. When these photons interact with the phosphor layers, this can take place as photoelectric interaction, coherent and incoherent (Compton) scattering. The total mass attenuation coefficient,  $\mu/\rho$ , of the phosphors can therefore be expressed as:

$$\mu/\rho = \tau/\rho + \sigma_{\text{coh}}/\rho + \sigma_{\text{C}}/\rho \quad (1)$$

where  $\tau/\rho$  is the photoelectric mass attenuation coefficient, and  $\sigma_{\text{coh}}/\rho$ ,  $\sigma_{\text{C}}/\rho$  are the mass attenuation coefficients for coherent scattering and Compton effect, respectively.

The mass attenuation coefficients for the phosphor materials of interest here are shown in Figures 1 to 8. In these presentations, the mass attenuation coefficients for Compton absorption and Compton scattering are shown separately. All mass attenuation coefficients are determined from tabulated coefficients of the elements composing the phosphors (Storm and

TABLE 1.

| Manufacturer | Trade name        | Phosphor                                                                              | Dominating<br>K-abs/keV |
|--------------|-------------------|---------------------------------------------------------------------------------------|-------------------------|
| Agfa-Gevaert | M.R. 50           | LaOBr:Tb                                                                              | 38.93                   |
|              | M.R. 200          | "                                                                                     | "                       |
|              | M.R. 400          | "                                                                                     | "                       |
|              | M.R. 600          | "                                                                                     | "                       |
| CAWO         | SE 2              | LaOBr:Tb                                                                              | 38.93                   |
|              | SE 4              | "                                                                                     | "                       |
|              | SE 6              | "                                                                                     | "                       |
| DuPont       | Cronex Par Speed  | CaWO <sub>4</sub>                                                                     | 69.53                   |
|              | Cronex Quanta II  | BaFCl:Eu                                                                              | 37.44                   |
| Fuji         | Grenex G-4        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   |
|              | Grenex G-8        | "                                                                                     | "                       |
| General El.  | Blue Max 1        | LaOBr:Tb                                                                              | 38.93                   |
|              | Blue Max 2        | "                                                                                     | "                       |
| Ilford       | Rare Earth        | LaOBr:Tm                                                                              | 38.93                   |
| Kodak        | X-Omatic Regular  | BaSO <sub>4</sub> :Eu/SrSO <sub>4</sub> :Eu                                           | 37.44/16.11             |
|              | Lanex Fine        | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   |
|              | Lanex Regular     | Gd <sub>2</sub> O <sub>2</sub> S:Tb/La <sub>2</sub> O <sub>2</sub> S:Tb <sup>1)</sup> | 50.24/38.93             |
| Philips      | Type 4360         | BaFCl:Eu                                                                              | 37.44                   |
|              | Type 6359         | "                                                                                     | "                       |
| Siemens      | Rubin Super       | CaWO <sub>4</sub>                                                                     | 69.53                   |
|              | Titan 923         | LaOBr:Tb                                                                              | 38.93                   |
| 3M           | Trimax Alpha 4    | Gd <sub>2</sub> O <sub>2</sub> S:Tb                                                   | 50.24                   |
|              | Trimax Alpha 8    | "                                                                                     | "                       |
| U.S.Radium   | Rarex BG Detail   | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>2)</sup>  | 50.24/17.04             |
|              | Rarex BG Mid Sp.  | Gd <sub>2</sub> O <sub>2</sub> S:Tb/Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>3)</sup>  | 50.24/17.04             |
|              | Rarex BG High Sp. | "                                                                                     | "                       |
|              | Rarex B Mid Sp.   | Y <sub>2</sub> O <sub>2</sub> S:Tb                                                    | 17.04                   |

1) 93 %/7 % by weight 2) 60 %/40 % by weight 3) 75 %/25 % by weight



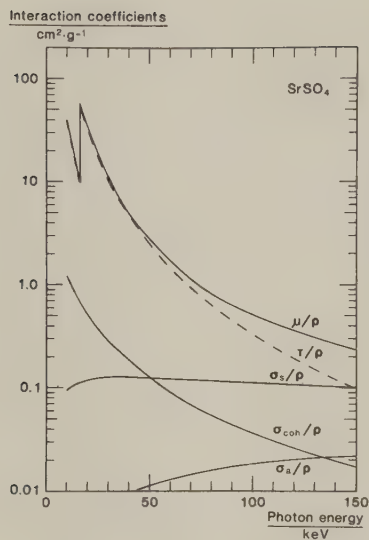


Figure 1. Interaction coefficients in strontium-sulphate

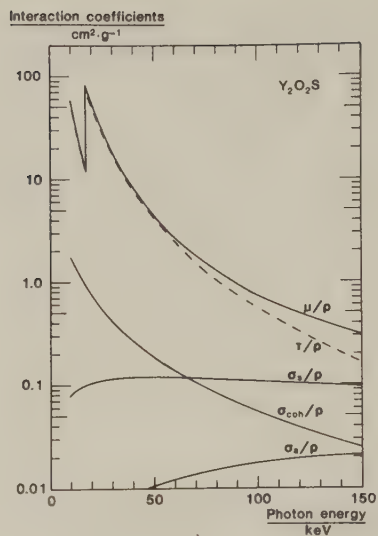


Figure 2. Interaction coefficients in yttrium-oxysulphide.

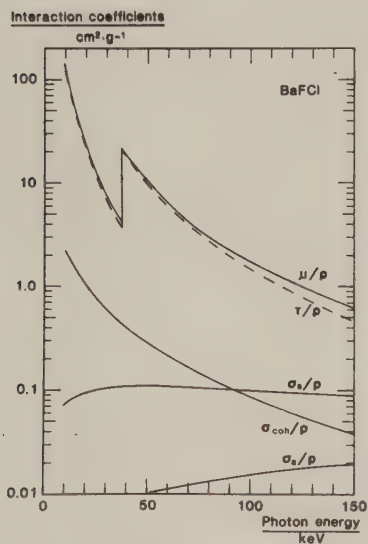


Figure 3. Interaction coefficients in barium-fluorochloride.

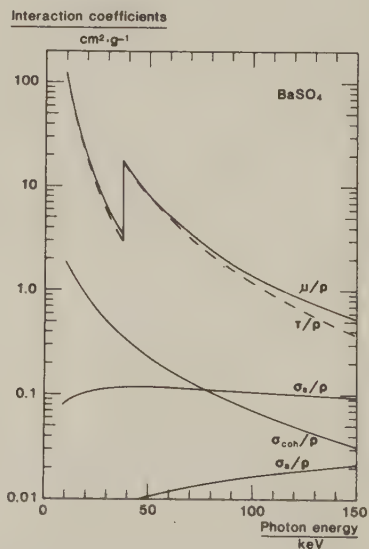


Figure 4. Interaction coefficients in barium-sulphate

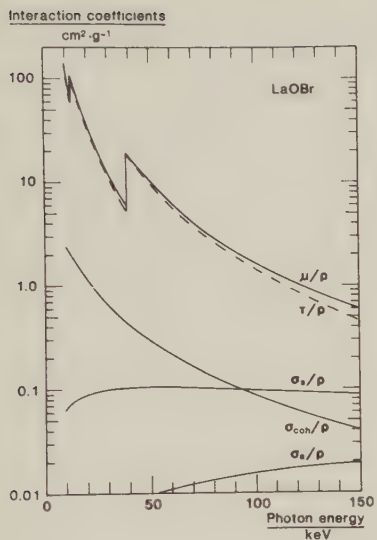


Figure 5. Interaction coefficients in lanthanum-oxbromide.

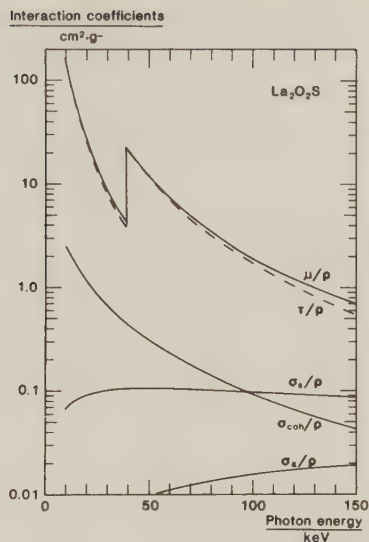


Figure 6. Interaction coefficients in lanthanum-oxysulphide.

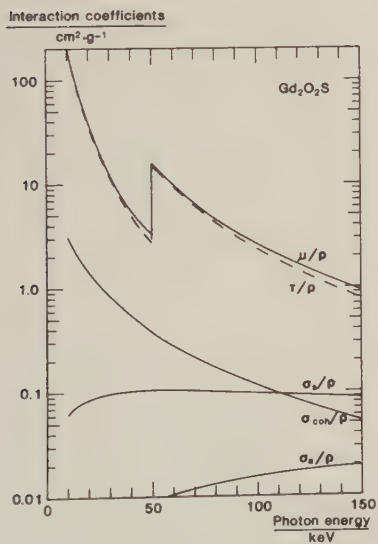


Figure 7. Interaction coefficients in gadolinium-oxysulphide.

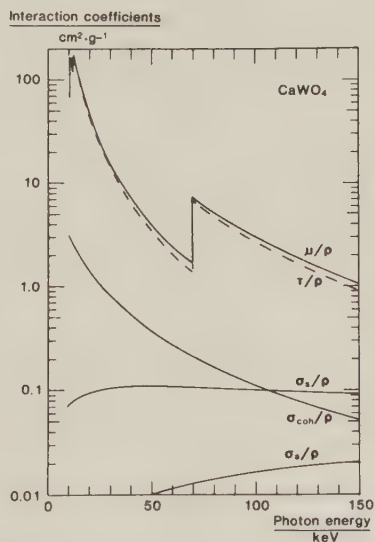


Figure 8. Interaction coefficients in calcium-tungstate.

Israel, 1967).

The majority of the photon interactions take place as photoelectric events in the high Z-element(s) of the phosphor materials. From this it is understood that the production of K x-rays may be considerable. The subsequent attenuation of these characteristic x-rays depends on the length of the path they cover in the phosphor material before they have a possibility to escape. This in turn is determined by the thickness of the screens and the emission site and the emission angle of the x-rays. While the emission site is determined by the character of the incident photons, the remainder of this complex attenuation is determined solely by the interaction characteristics between the produced x-rays and the phosphor layers.

The production and subsequent attenuation of K x-rays have been calculated according to a model published by Shuping and Judy (1977) and Vyborny et al. (1978). These determinations utilize the experimentally determined attenuation of monoenergetic photons by the intensifying screens (Holje, 1983 a). According to the model, the screen-pair thickness is divided into thin layers and the production of x-rays in each layer is determined. The length of their path within the phosphor layer at different angles of emittance is then determined. The solid angle is hereby divided into small elements, and the mean distance to the screen surfaces is determined for each element. Measured attenuation properties of the screens are utilized to determine the attenuation of x-rays in each element of the solid angle. The attenuation of x-rays produced in the entire screen pair is obtained after integration over the entire sphere and the screen thickness.

The attenuation of fluorescent K x-rays was calculated in this investigation for thin screen layers equal to 1/50th of the total screen pair thickness and for small solid angle elements equal to 1/50th of  $\pi$ . The use of thinner layers and/or smaller solid angle elements was found to have no effect on the results. The determinations were performed for incident photon energies ranging from the K absorption edge of the high Z-element of the phosphor to 120 keV. The emitted  $K_{\alpha}$  and  $K_{\beta}$  radiation was treated as a monoenergetic beam of radiation with energy corresponding to the weighted average of the emitted K x-ray energies (Storm and

Israel, 1967). This simplification was done since calculations of the energy deposited by the K x-rays, using this approximation, gave the same results as those obtained, when the  $K_{\alpha}$  and  $K_{\beta}$  energies were treated separately.

## 2.2 Determinations of the energy absorption of fluorescent K x-rays produced in the screens.

When the K x-rays interact with the phosphor material, a fraction of their energy may escape as scattered radiation. Only that fraction of the K x-ray energy, remaining in the screens is of importance, and therefore the energy absorption, rather than the attenuation of the K x-rays, is of greatest interest here.

Figures 1 to 8 show that photoelectric absorption dominates by far over Compton absorption at all photon energies below the K-absorption edge of the high atomic element of the phosphors. Only the photoelectric absorption will, therefore, be considered in the following. It is further assumed that all characteristic radiation, except for the K x-rays emanating from the highest Z-element, is totally absorbed by the phosphor material. These lower energy x-rays consist of L x-rays of the highest Z-element and of K x-rays of the lower Z-element of the phosphor. In phosphors with only one high Z-element, their mean free paths (Storm and Israel, 1967) are of the order or the crystal size.\* These x-rays can, therefore, very well be considered as totally absorbed (Holje, 1983 b). Some phosphors, however, such as  $\text{LaOBr}$ ,  $\text{BaSO}_4/\text{SrSO}_4$  and  $\text{Gd}_2\text{O}_2\text{S}$  mixed with  $\text{La}_2\text{O}_2\text{S}$  or  $\text{Y}_2\text{O}_2\text{S}$ , have two higher Z-elements. - "Higher Z" alludes to elements with K-absorption edges around 15 keV or higher.-. In these phosphors, the second highest energy K x-rays also have a certain probability to escape from the phosphor screens. The assumptions that they are totally absorbed will, therefore, introduce some errors in the determinations of the energy absorption of the highest energy K x-rays. In screens made of  $\text{LaOBr}$ ,  $\text{BaSO}_4/\text{SrSO}_4$  or  $\text{Gd}_2\text{O}_2\text{S}/\text{Y}_2\text{O}_2\text{S}$ , the calculated energy absorption is overestimated by less than 1 %. In the Lanex Regular screens, which are composed of 93 %  $\text{Gd}_2\text{O}_2\text{S}$  and 7 %  $\text{La}_2\text{O}_2\text{S}$ , the overesti-

\* Information about phosphor density and crystal size has been supplied by the manufacturers.

mation, is, however as high as 4 %, despite the low content of lanthanum. This is due to the high energy of the lanthanum K x-rays, which is about 75 % of that of the gadolinium K x-rays. Their mean free path in the phosphor material is, further, fairly high. In gadolinium K x-ray interactions, which give rise to lanthanum K x-rays, therefore, a large fraction of energy is transferred to secondary K x-rays, which are quite likely to escape. The overestimation by 4 % of the energy absorption of gadolinium K x-rays is not considered to be of decisive importance, however, since only one screen pair is concerned, and since the manufacturing of these mixed phosphor screens has ceased.

With these assumptions concerning the energy transfer from K x-rays to the phosphor material, the mass energy absorption coefficients,  $\mu_{en}/\rho$  can be expressed as:

$$\mu_{en}/\rho = \tau_a/\rho + \sigma_a/\rho \approx \tau_a/\rho = \tau/\rho \cdot E/h\nu \approx \tau/\rho \quad (2)$$

where  $h\nu$ , is the K x-ray energy and  $E$  is the average energy transferred to the medium per photoelectrically absorbed K x-ray photon.

Using the coefficients in Equations 1 and 2, the attenuation,  $A_K$ , and the energy absorption,  $B_K$ , of the fluorescent K x-rays can be expressed as:

$$A_K = 1 - e^{-\mu/\rho \cdot \bar{d}} \quad (3)$$

$$B_K = 1 - e^{-\tau/\rho \cdot \bar{d}} \quad (4)$$

where  $A_K$  is the attenuation, determined according to the model described in Section 2.1, and  $\bar{d}$  is the mean thickness of the phosphor layer traversed by the internally produced K x-rays.



By combining Equations 3 and 4, the following expression for the energy absorption is obtained:

$$B_K = A_K \cdot \frac{1 - e^{-\tau/\rho \cdot \bar{d}}}{1 - e^{-\mu/\rho \cdot \bar{d}}} \approx A_K \cdot \frac{\tau/\rho}{\mu/\rho} \quad (5)$$

Here, the first order approximations of the exponential expressions have been utilized. This facilitates the calculations, since no estimations of the effective screen thicknesses have to be performed. The approximation in Equation 5 is, however, possible only because of the comparable absolute values of the two exponents. The fractional overestimation introduced, by rejecting the higher order terms, is only somewhat smaller in the nominator than in the denominator, yielding a value of the approximated quotient, which is only slightly underestimated. By employing the actual screen thicknesses (Holje, 1983 a), the underestimations are estimated to be between -1.5 % and -3 %. The larger deviations are found in the thicker screens. In the yttrium oxysulphide screens, however, the underestimation is about -4.5 %. These slight underestimations of the energy absorptions of fluorescent K x-rays in the screens have not been considered to be of vital importance.

### 2.3 Contribution of absorbed K x-ray energy to the total energy absorbed by the screens.

The K x-ray energy absorption,  $B_K$ , in the intensifying screens expresses the fraction of emitted x-ray energy, which is reabsorbed by the screens. The impact of absorbed K x-ray energy is, however, clearly seen only when it is related to the incident photon energy or to the total energy absorbed by the screens. The quantity, which is of importance for the understanding of its effect on sensitivity, noise and resolution properties of screen film systems, is the contribution of K x-ray energy to the total energy absorbed by the screens. This quantity has been studied for the screen-film systems, when they are exposed to broad x-ray distributions (Holje, 1983 b). A more fundamental evaluation will be made here by studying the K x-ray contribution,  $B_K$ , to the total energy absorption,  $B$ , when intensifying screens are exposed to monoenergetic photons. These

determinations will be made using the following expression (Holje, 1983 b):

$$\frac{B_4}{B} = \frac{\frac{v \cdot (\tau/\rho)_{h.a.} \cdot \tau_K/\tau \cdot \omega_K \cdot B_K \cdot E_4/h\nu}{(\mu/\rho)_{tot}}}{\frac{(\tau/\rho)_{tot}}{(\mu/\rho)_{tot}} - \frac{v \cdot (\tau/\rho)_{h.a.} \cdot \tau_K/\tau \cdot \omega_K \cdot (1-B_K) \cdot E_4/h\nu}{(\mu/\rho)_{tot}}} \quad (6)$$

- $B$  is the fraction of incident photon energy, which is deposited in the screens,
- $B_4$  is the fraction of incident photon energy, which is deposited in the screens by internally produced K x-rays,
- $(\tau/\rho)_{h.a.}$  is the photoelectric mass attenuation coefficient of the high Z-element of the phosphor,
- $v$  is the fraction by weight of the high Z-element,
- $(\mu/\rho)_{tot}$  is the mass attenuation coefficient of the phosphor,
- $\tau_K/\tau$  is the relative K-shell contribution to the photoelectric cross-section,
- $\omega_K$  is the K-fluorescent yield,
- $B_K$  is the energy absorption of the K x-rays,
- $E_4$  is the weighted average of the K x-ray energies,
- $h\nu$  is the incident photon energy, and
- $(\tau/\rho)_{tot}$  is the photoelectric mass attenuation coefficient of the phosphor.

### 3. RESULTS AND DISCUSSION

#### 3.1 Attenuation of internally produced K x-rays.

It was mentioned in Section 2.1 that the origin of the K x-rays within the screens influences the length of their path in the phosphor material and thus the probability for interactions. The immediate consequence of this is that the attenuation of K x-rays is affected by the distribution of production sites throughout the screens, i.e. by the incident photon energy. Calculations of the K x-ray attenuation at various photon energies, however, show that it is almost independent of the energy of incident photons. This applies to all of the screens studied. The same, very slight, energy dependence has been reported by others (Shuping and Judy, 1977; Vyborny et al., 1978). Except for a slight decrease at low incident photon energies, the K x-ray attenuation adopts a constant value over the whole range of the incident photon energies studied. The slight decrease is a result of the fact that a comparatively large fraction of K x-rays is produced at the screen surface at low incident photon energies, and this increases their probability for escape.

The finding that the attenuation of the K x-rays is not affected by the energy of the incident photons considerably simplifies determinations of the energy absorption in the intensifying screens, especially when they are exposed to broad x-ray distributions (Holje, 1983 b).

The attenuation of K x-rays in the intensifying screens incorporated in this study,  $A_K$ , is presented in Table 2, column 3. The experimentally determined attenuation of perpendicularly incident photons,  $A_{h\nu = K}$  (Holje, 1983 a), which has been utilized in the calculations, is presented in Table 2, column 2. It is obvious that the attenuation of internally produced K x-rays is different from the attenuation of incident photons of equivalent energy. In almost all of the screens, the attenuation is higher when the radiation is emitted within the screens. In those screens only with very high attenuation (more than 55 %), the attenuation of internally produced photons is lower than that of perpendicularly incident photons.

In Figure 9, the calculated attenuation of K x-rays in all of the inten-

TABLE 2

| Intensifying screens | K x-ray en.<br>$K_{\alpha,\beta}/\text{keV}$ | Att.<br>$A_{h\nu=K}$ | Att.<br>$A_K$ | En.Abs.<br>$B_K$ |
|----------------------|----------------------------------------------|----------------------|---------------|------------------|
| M.R. 50              | 34.275                                       | 0.42                 | 0.46          | 0.43             |
| M.R. 200             | "                                            | 0.49                 | 0.52          | 0.48             |
| M.R. 400             | "                                            | 0.45                 | 0.48          | 0.45             |
| M.R. 600             | "                                            | 0.64                 | 0.62          | 0.57             |
| Rare Earth           | "                                            | 0.46                 | 0.50          | 0.46             |
| Titan 923            | "                                            | 0.58                 | 0.57          | 0.53             |
| Cronex Quanta II     | 32.988                                       | 0.41                 | 0.46          | 0.41             |
| Type 4360            | "                                            | 0.34                 | 0.41          | 0.36             |
| Type 6359            | "                                            | 0.44                 | 0.48          | 0.43             |
| X-Omatic Regular     | "                                            | 0.51                 | 0.53          | 0.48             |
| Cronex Par Speed     | 60.936                                       | 0.14                 | 0.22          | 0.19             |
| Rubin Super          | "                                            | 0.17                 | 0.26          | 0.21             |
| Grenex G-4           | 44.132                                       | 0.31                 | 0.38          | 0.33             |
| Grenex G-8           | "                                            | 0.40                 | 0.45          | 0.39             |
| Lanex Fine           | "                                            | 0.27                 | 0.35          | 0.30             |
| Lanex Regular        | "                                            | 0.49                 | 0.52          | 0.45             |
| Trimax Alpha 4       | "                                            | 0.25                 | 0.33          | 0.29             |
| Trimax Alpha 8       | "                                            | 0.41                 | 0.46          | 0.40             |
| Rarex BG Detail      | 44.132                                       | 0.34                 | 0.41          | 0.37             |
| Rarex BG Mid Sp.     | "                                            | 0.46                 | 0.50          | 0.44             |
| Rarex BG High Sp.    | "                                            | 0.56                 | 0.56          | 0.50             |
| Rarex B Mid Sp.      | 15.204                                       | 0.90                 | 0.79          | 0.74             |

## Attenuation of internally produced photons

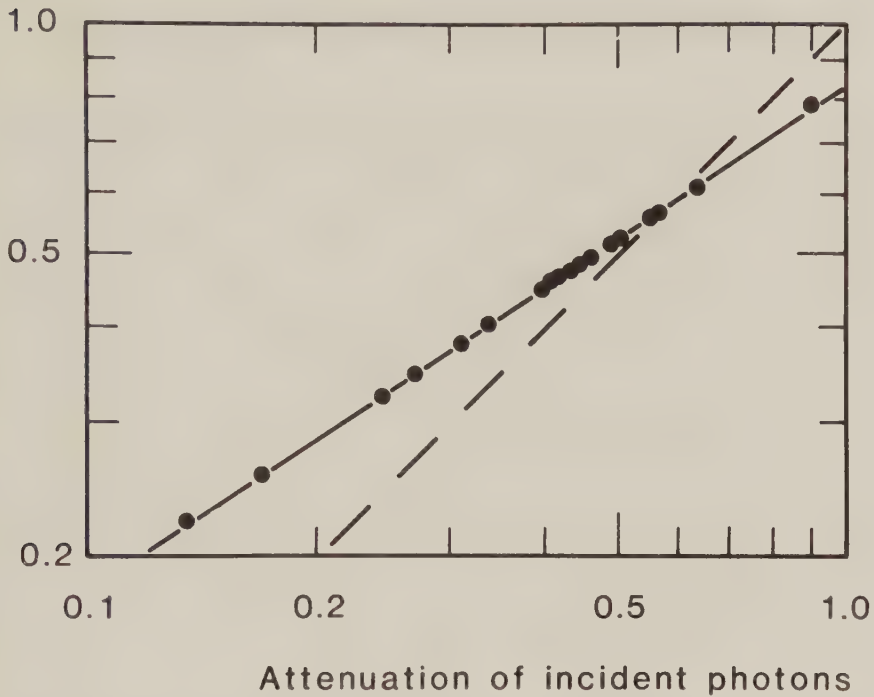


Figure 9. Attenuation of photons internally produced in the screens versus their attenuation of perpendicularly incident photons of equivalent energy. ----- indicates equality between the two attenuations. ——— is fitted by regression analysis to the values on the separate screens.

sifying screens is plotted versus the measured attenuation of incident photons. The two attenuations exhibit a linear relationship in log-log terms. This can be expressed by the following equation:

$$\log A_K = 0.67 \cdot \log(A_{h\nu=K}) - 0.079 \quad (7)$$

This relationship is by far much simpler than that derived by Shuping and Judy (1977) and Vyborny (1978). It is obvious from Equation 7, that the K x-ray attenuation can be determined without complex calculations of the K x-rays origins and the subsequent lengths of their paths within the screen phosphor. The only factor which has to be known is the attenuation by the screens of external photons with the same energy as that



of the K x-rays.

Equation 7 can thus be rewritten as:

$$\log A_K(d) = 0.67 \cdot \log (1 - e^{-\mu/\rho \cdot d}) - 0.079 \quad (8)$$

where  $\mu/\rho$  is the mass attenuation coefficient of the phosphor material at the K x-ray energy, and  $d$  is the screen thickness.

From Equation 8, the attenuation of K x-rays in intensifying screens of any thickness can easily be calculated. This possibility will be utilized in Section 3.2 for determinations of the energy absorption of K x-rays in screens of equal thickness but with different chemical composition.

### 3.2 Energy absorption of K x-rays.

Table 2, column 4, shows the calculated K x-ray energy absorption in the screen pairs. The highest value, 0.74, is found in the B Mid screens of yttrium oxysulphide and the lowest, about 0.20, is found in the two calcium tungstate screens. The K x-ray energy absorption in the other screens adopts values between 0.30 and 0.60.

In Figure 10, these energy absorptions of K x-rays are plotted versus the screen pair thicknesses (Holje, 1983 a). The curves in Figure 10 have been derived using calculated K x-ray attenuations in screens of different thicknesses (Equation 8). The good agreement between the values for the separate screens and the curves proves that it is possible to make reliable predictions of the K x-ray energy absorption by using attenuation derived from Equation 8.

Shuping and Judy (1977) investigated the K x-ray energy absorption in calcium tungstate screens of varying thicknesses. They report the value 0.26 for a  $100 \text{ mg/cm}^2$  thick screen pair. The corresponding value obtained here, 0.25, agrees very well with Shuping and Judy's findings. The Cronex Par Speed screens and the X-Omatic Regular screens were incorporated in Vyborny's investigation. Vyborny (1978) reported  $K_\alpha$  - and  $K_\beta$  -energy absorption separately. When the two values are added, by taking the relative K x-ray intensities into account (Storm and Israel, 1967), the K x-ray energy absorption is 0.20 in the Par Speed screens, and 0.48 in the X-Omatic Regular screens. The values derived here are 0.19 and 0.48 res-

## Energy absorption of K x-rays

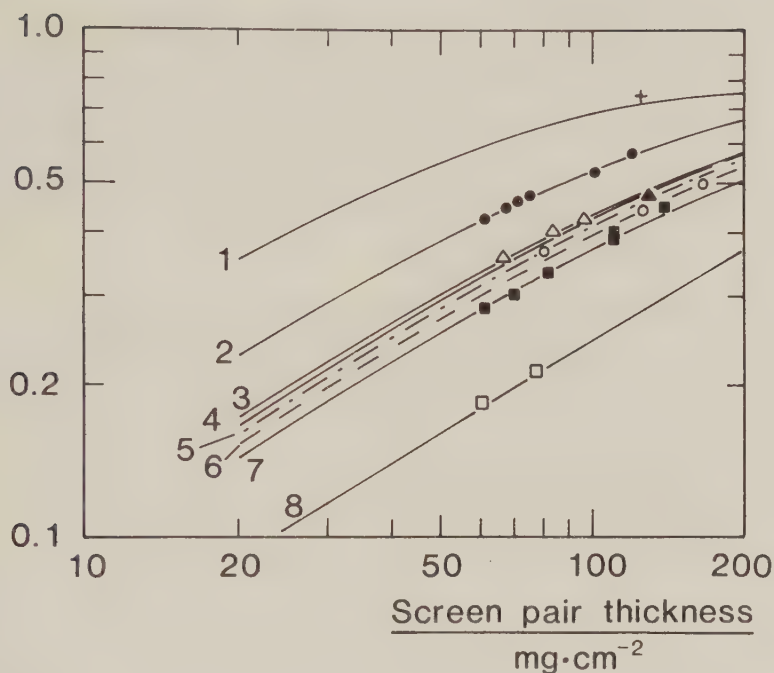


Figure 10. Energy absorption of K x-rays produced in the screens versus their thicknesses. Calculated relationships for screens of different chemical compositions are shown by the curves and the evaluated relationships for the separate screens are indicated by symbols.  
 1 and + —  $\text{Y}_2\text{O}_3$ -screens, 2 and ● —  $\text{LaOBr}$ -screens, 3 and  $\Delta$  —  $\text{BaFCl}$ -screens  
 4 and  $\blacktriangle$  —  $\text{BaSO}_4/\text{SrSO}_4$ -screens, 5, 6 and ○ —  $\text{Gd}_2\text{O}_3/\text{Y}_2\text{O}_3$ -screens,  
 7 and  $\blacksquare$  —  $\text{Gd}_2\text{O}_3$ -screens, 8 and  $\square$  —  $\text{CaWO}_4$ -screens.

pectively, which is in good agreement with Vyborny's findings.

It is clearly demonstrated in Figure 10 that the K x-ray absorption is high in phosphors composed of low Z-elements. This is an immediate consequence of the fact that the transparency of an element to its characteristic radiation decreases rapidly with decreasing atomic number (Storm and Israel, 1967). Since the energy of the characteristic radiation produced in a low Z-element is low, only a small amount of energy will be deposited at each absorption event. The impact of the absorption of K x-rays is, therefore, difficult to establish solely from analysis of the K x-ray energy absorption.

### 3.3 Contribution of absorbed K x-ray energy to the total energy absorbed by the screens.

The contribution of K x-ray energy to the total energy absorbed was calculated for five  $100 \text{ mg/cm}^2$  screens of different chemical compositions. The energy absorptions of K x-rays in these screens,  $B_K$ , in Equation 6, were obtained from Figure 10. The determinations were performed at various photon energies, ranging from the K-absorption edge of the high Z-element of the phosphor materials to 120 keV.

The results, presented in Figure 11, show that the contribution of K x-ray energy to the total energy absorbed is highest at photon energies just above the K-absorption edge of the high Z-element of the phosphors.

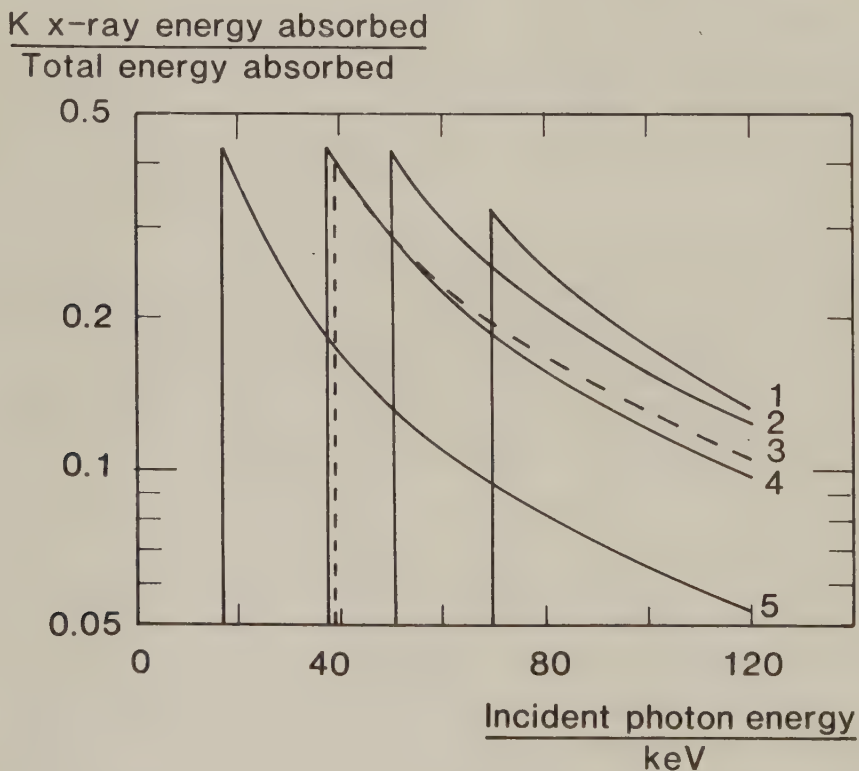


Figure 11. Contribution of K x-ray energy to the total energy absorbed in  $100 \text{ mg} \cdot \text{cm}^{-2}$  thick screens when exposed to monoenergetic radiation. 1.  $\text{CaWO}_4$ -screens, 2.  $\text{Gd}_2\text{O}_2\text{S}$ -screens, 3.  $\text{LaOBr}$ -screens, 4.  $\text{BaFCl}$ -screens, 5.  $\text{Y}_2\text{O}_2\text{S}$ -screens.

At these photon energies, the K x-ray contribution in screens made of the new phosphors is as high as 0.4. It is somewhat lower in the screen-pair made of calcium tungstate. These high values result from the fact that almost all incident photon energy is transferred to the K x-rays. As the incident photon energy increases, less fractional energy is transferred to the K x-rays. This results in the gradual decreases of the K x-ray contributions to the total absorbed energies which are apparent in Figure 11.

It is obvious from the presentation in Figure 11, that the incident photon energy is of significant importance when comparing the K x-ray contribution to the total energy absorbed in screens made of the different phosphors. As soon as the incident photon energy exceeds that of the K-absorption edge in any of these phosphor screens, that specific screen attains the highest K x-ray contribution to the total absorbed energy. To provide a relevant comparison of these five screens, it is apparent that respect must be paid to their different K-absorption energies. It is interesting to see that the K x-ray contribution in all of the screens, except for that in the  $Y_2O_2S$ -screens, has decreased to between 60 - 70 % of its initial value, when the incident photon energy exceeds that of the K-absorption edge by 50 keV. - The decrease in the yttrium oxysulphide screens is larger. - It can, therefore, be concluded that the "ability" to absorb K x-ray energy is not larger in the new screen phosphors than in the calcium tungstate phosphor. The high contribution of K x-ray energy to the total absorbed energy, found in most of the new screens (Holje, 1983 b), is an effect of the favourable matchings between the photon distributions employed and the energy absorption properties of the screens.

## REFERENCES

Arnold B.A. and Bjärngård B.E., 1979.

The effect of phosphor K X-rays on the MTF of rare-earth screens.  
Medical Physics 6(6):500-503.

Buchanan R.A., Finkelstein S.I. and Wickersheim K.A., 1972.

X-Ray exposure reduction using rare-earth oxysulfide intensifying screens.  
Radiology 105:185-190.

Holje G., 1983 a.

Photon attenuation by radiographic intensifying screens.

CODEN Report LUNFD6 (NFRA-3033) / LUMEDW (MERI-3033), Dept. of Radiation  
Physics, Lund University, Lund, Sweden.

Holje G., 1983 b.

Energy absorption in radiographic intensifying screens.

CODEN Report LUNFD6 (NFRA-3034) / LUMEDW (MERI-3034), Dept. of Radiation  
Physics, Lund University, Lund, Sweden.

Holje G., 1983 g.

Physical properties of radiographic screen-film systems. Doctoral thesis.  
Dept. of Radiation Physics, Lund University, Lund, Sweden.

Holje G., Svahn G., Hårdstedt C., Ramnhagen A., Öberg A. and Forsberg H.,  
1977.

Intensifying screens for X-ray cassettes, performance, usability, etc.  
(in Swedish, English summary).

The Swedish Institute for the Planning and Rationalization of Health and  
Social Welfare Services Publication S 67.

Holje G. and Doi K., 1982.

MTF's and Wienerspectra of radiographic screen-film systems. Part 2.

Sensitivity, sensitometry, resolution and noise characteristics of new



screen-film systems.

U.S. Department of Health and Human Services Publication FDA 82-8187,  
Bureau of Radiological Health, Rockville, Maryland 20857.

Karlsson M., Wickman G. and Hettinger G., 1977.

Characteristics of X-ray screen phosphor at photon energies between  
20 - 140 keV.

Paper presented at the 9th Nordic Meeting of Clinical Physics, Gothenburg,  
Sweden.

Shuping R.E. and Judy P.F., 1977.

Energy absorbed in calcium-tungstate X-ray screens.  
Medical Physics 4(3):239-243.

Storm E. and Israel H.J., 1967.

Photon cross sections from 0.001 to 100 MeV for elements 1 through 100.  
Los Alamos scientific laboratory of the University of California.  
LA-3753, U C-34, Physics, TID-4500.

Vyborny C.J., Metz C.E., Doi K. and Haus A., 1978.

Calculated characteristic X-ray reabsorption in radiographic screens.  
Journal of Applied Photographic Engineering 4(4):172-177.

Vyborny C.J., Loo L.N. and Doi K., 1982.

The energy-dependent behaviour of noise Wiener spectra in their low-  
frequency limits: Comparison with simple theory.  
Radiology 144(3):619-622.



Dokumentutgivare  
Inst för radiofysik  
Handläggare  
Författare  
Gunnila Holje

Dokumentnamn  
CODEN Report  
Utgivningsdatum  
April 1983

Dokumentbeteckning  
3038  
Ärendebeteckning

Dokumenttitel och undertitel

COEFFICIENTS FOR CONVERTING X-RAY EXPOSURE TO PHOTON FLUENCE AND ENERGY FLUENCE

A determination of conversion coefficients covering a broad range of radiation distributions, simulating those which are transmitted through the object in various diagnostic X-ray examinations.

Referat (sammandrag)

Coefficients for converting X-ray exposure to photon fluence and energy fluence have been determined for radiation distributions, which impinge on image recording systems used in diagnostic X-ray examinations. Aluminium is chosen to simulate human tissue, since the radiation distribution behind a certain amount of water can be simulated by using aluminium filter. The coefficients for converting X-ray exposure to photon fluence and energy fluence are determined for twenty radiation distributions, produced at different X-ray tube potentials and with various aluminium filter thicknesses. Weighted mass energy absorption coefficients of air are also determined for these radiation distributions, since these can substitute exposure-to-energy fluence conversion coefficients.

Referat skrivet av

Förslag till ytterligare nyckelord

Klassifikationssystem och -klasser

Index termer (ange källa)

Omfattning

Övriga bibliografiska uppgifter

Språk

Sekretessuppgifter

ISSN

ISSN

Dokumentet kan erhållas från

Mottagarans uppgifter

Inst för radiofysik vid Lunds universitet  
Lasarettet  
S-221 85 LUND

Pris

115  
DS 1

OKUMENTDATATABLAD enligt SIS 02 10 12

Blankett LU 11:25 1976-07



# COEFFICIENTS FOR CONVERTING X-RAY EXPOSURE TO PHOTON FLUENCE AND ENERGY FLUENCE

A determination of conversion coefficients covering a broad range of radiation distributions, simulating those which are transmitted through the object in various diagnostic x-ray examinations

Gunnilla Holje

Lund 1983





| <u>CONTENTS</u>                                 | Page |
|-------------------------------------------------|------|
| 1. INTRODUCTION.....                            | 1    |
| 2. CALCULATIONS OF CONVERSION COEFFICIENTS..... | 1    |
| 2.1 The radiation distributions                 | 1    |
| 2.2 The equations                               | 4    |
| 3. RESULTS AND DISCUSSION .....                 | 7    |
| REFERENCES.....                                 | 12   |



## 1. INTRODUCTION

The ionization chamber is a simple and widely used detector of ionizing radiation. The radiation exposure,  $X$ , is frequently, however, not the quantity which is of immediate interest. Conversions must, therefore, be performed to yield appropriate quantities. These conversions, which may be quite simple when monoenergetic radiation is concerned, can be fairly complicated when radiation distributions are involved.

This study is concerned with radiation distributions which impinge on image-recording systems used in x-ray diagnostic examinations. These distributions are strongly influenced by the x-ray tube potential, but equally important factors are the thickness, density and atomic number of the object. Aluminium is chosen in this investigation for simulating human tissue, since the  $HVL_X$  of the radiation behind a certain amount of water can be simulated by using aluminium filter (Mika and Reiss, 1973). Coefficients for converting x-ray exposure to photon fluence and energy fluence will be determined for twenty radiation distributions, produced at different x-ray tube potentials and with various aluminium filter thicknesses. Weighted mass energy absorption coefficients of air will also be determined, since these can substitute exposure to energy fluence conversion coefficients.

## 2. CALCULATIONS OF CONVERSION COEFFICIENTS

### 2.1 The radiation distributions.

The radiation distributions were produced at 60, 80, 100 and 120 kV using object-simulating filters of 5, 10, 15, 20 and 25 mm aluminium. Since scattered radiation was excluded in the determinations, the conditions are idealized and equivalent to clinical situations where no scattered radiation is allowed to reach the image recorder. Aluminium was chosen since the  $HVL_X$  of the radiation behind a certain amount of water can be simulated by using an aluminium filter with a thickness equal to 0.08 of the water. This is shown in Figure 1, where the  $HVL_X$ 's at 60, 80, 100 and 120 kV tube potential are plotted versus the thicknesses of water and aluminium (Mika and Reiss, 1973). Figure 1 shows that there is good agreement between the  $HVL$ 's behind water and aluminium over a wide range of thicknesses and x-ray tube potentials. Note especially that the  $HVL_X$  be-

HVL aluminium  
mm

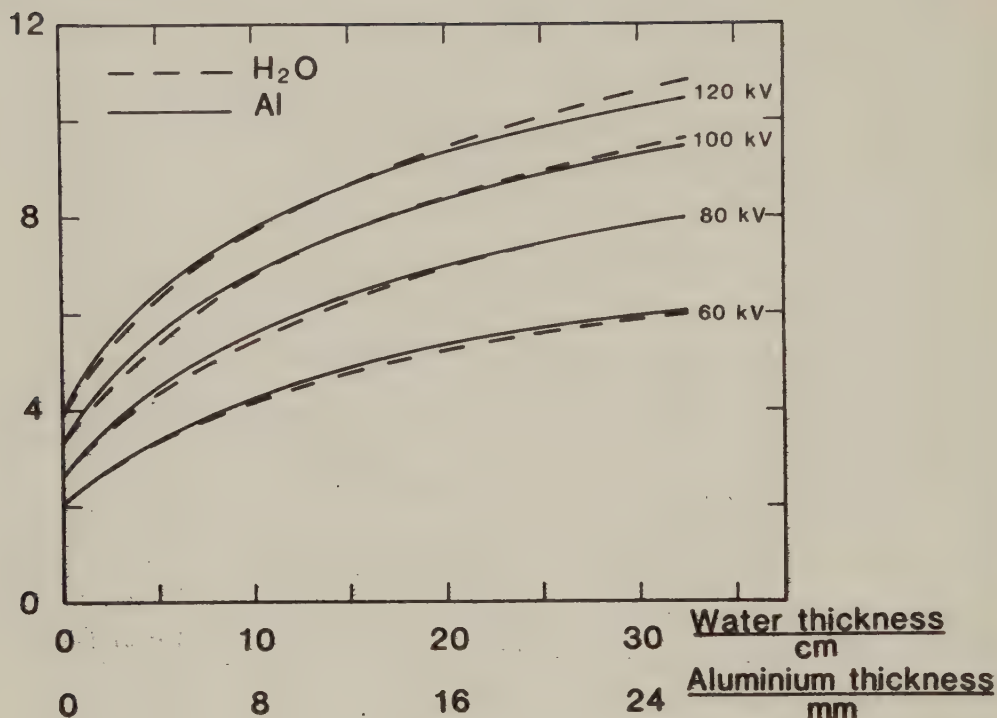


Figure 1. Exposure half-value layer in aluminium of radiation distributions behind water and aluminium at various x-ray tube potentials.

hind 20 mm aluminium is the same as that behind 25 cm water at the tube potential of 80 kV. This radiation quality is often used as a reference radiation quality (Holje, 1983 a, b, c, d).

An extensive investigation of diagnostic x-ray spectra has been made by Svahn (1977). His work was carried out with a 12-pulse coupled 3-phase generator with 12 rectifiers. The x-ray tube had a rotating anode consisting of an alloy of tungsten and rhenium (Siemens Biangulix Rapide Bi 150/30/50 R). The inherent filtration of the x-ray tube, the housing and the diaphragm was specified by the manufacturer to be equivalent to at least 2 mm aluminium. An additional filter of 0.5 mm aluminium was used in the measurements. The total filtration with this arrangement was estimated to be equivalent to 3.2 mm aluminium at 70 kV (Svahn, 1977).



Measured x-ray distributions emitted at 60, 80, 100 and 120 kV constant potentials\* (Svahn, 1977) were used in the calculations. The radiation distributions transmitted through the various filters were calculated by applying exponential attenuation (Hubbell, 1969) in the aluminium. Since Svahn's work also included measured x-ray spectra at 60, 80, 100 and 120 kV filtered with 20 mm aluminium (Acoa type 1060, 99.9 % Al), the validity of the calculations could be verified. An example of the good agreement between measured and calculated photon distributions is shown in Figure 2, where the x-ray distribution at 80 kV filtered with 20 mm

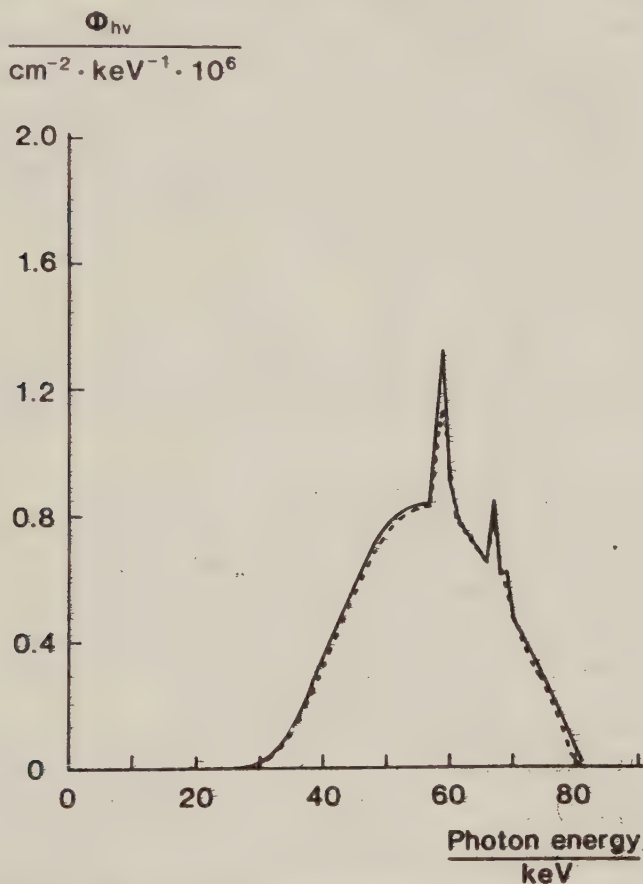


Figure 2. Photon distribution transmitted through 20 mm aluminium at x-ray tube potential 80 kV. ----- Measured distribution (Svahn, 1977), ——— Calculated from measured incident distribution (Svahn, 1977) by applying exponential attenuation in the aluminium.

\* The high tension pulsation introduced at high tube currents used in x-ray exposures will only result in a minor change of these photon distributions (Svahn, 1977).

aluminium is presented. Figures 3 to 6 show the calculated photon distributions of the twenty radiation qualities employed in this study. All photon fluence spectra are normalized to an exposure of  $0.258 \mu\text{C}\cdot\text{kg}^{-1}$  (1 mR).

## 2.2 The equations.

The x-ray exposure,  $X$ , is expressed as:

$$X = (e/W_{\text{air}}) \cdot \Psi \cdot (\mu_{\text{en}}/\rho)_{\text{air}} \quad (1)$$

where  $e$  is the elementary charge,  $W_{\text{air}}$  is the mean energy needed for the production of one ion pair in air and  $(\mu_{\text{en}}/\rho)_{\text{air}}$  is the mass energy absorption coefficient of air (Hubbell, 1969). The energy fluence,  $\Psi$  appearing in Equation 1 is the quantity into which the exposure will be converted. The conversion coefficient,  $(\Psi/X)$ , for monodenergetic radiation is therefore derived from Equation 1 as:

$$(\Psi/X) = (W_{\text{air}}/e) \cdot (\mu_{\text{en}}/\rho)_{\text{air}}^{-1} \quad (2)$$

When photon distributions are involved, the conversion coefficient is derived from:

$$\begin{aligned} (\Psi/X)_{x,y} &= (W_{\text{air}}/e) \frac{\int_{h\nu_{\text{min}}}^{h\nu_{\text{max}}} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} dh\nu}{\int_{h\nu_{\text{min}}}^{h\nu_{\text{max}}} \left(\frac{d\Psi}{dh\nu}\right)_{x,y} \cdot (\mu_{\text{en}}/\rho)_{\text{air}} dh\nu} = \quad (3) \\ &= (W_{\text{air}}/e) \cdot (\mu_{\text{en}}/\rho)_{\text{air},x,y}^{-1} \end{aligned}$$

where  $\left(\frac{d\Psi}{dh\nu}\right)_{x,y}$  is the differential energy fluence at  $x$  kV filtered with  $y$  mm aluminium,  $(\mu_{\text{en}}/\rho)_{\text{air},x,y}$  is the mass energy absorption coefficient weighted according to the energy fluence distribution produced at  $x$  kV filtered with  $y$  mm aluminium and  $h\nu_{\text{min}}$  and  $h\nu_{\text{max}}$  are the lowest and highest photon energies of the distributions.

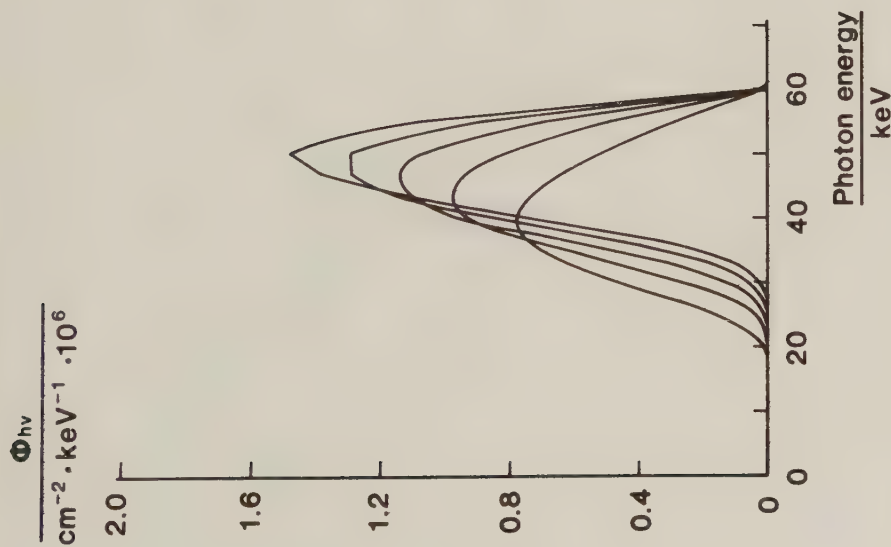


Figure 3. Photon distributions transmitted through 5, 10, 15, 20 and 25 mm aluminium at x-ray tube potential 60 kV

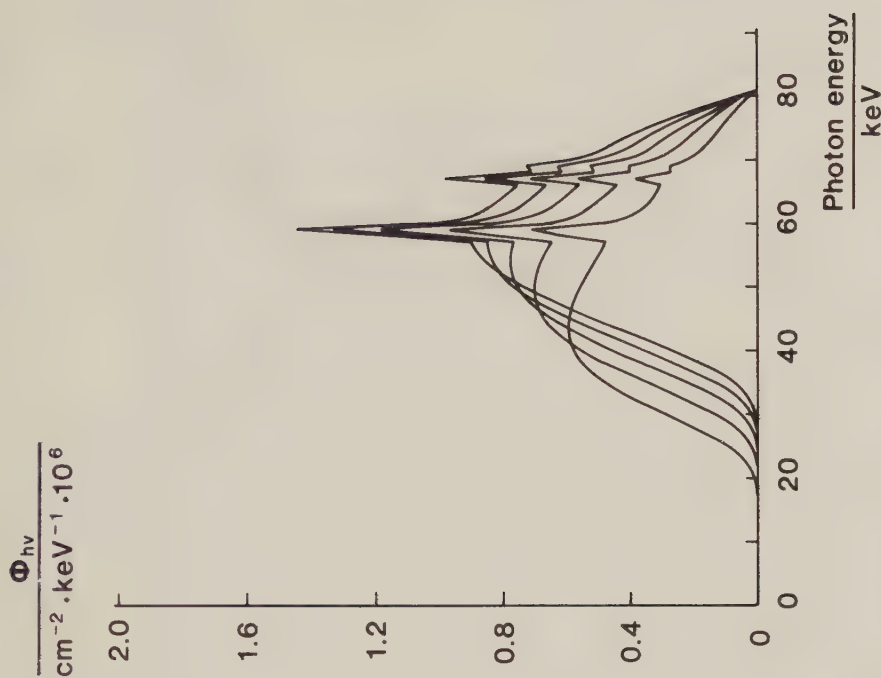


Figure 4. Photon distributions transmitted through 5, 10, 15, 20 and 25 mm aluminium at x-ray tube potential 80 kV.

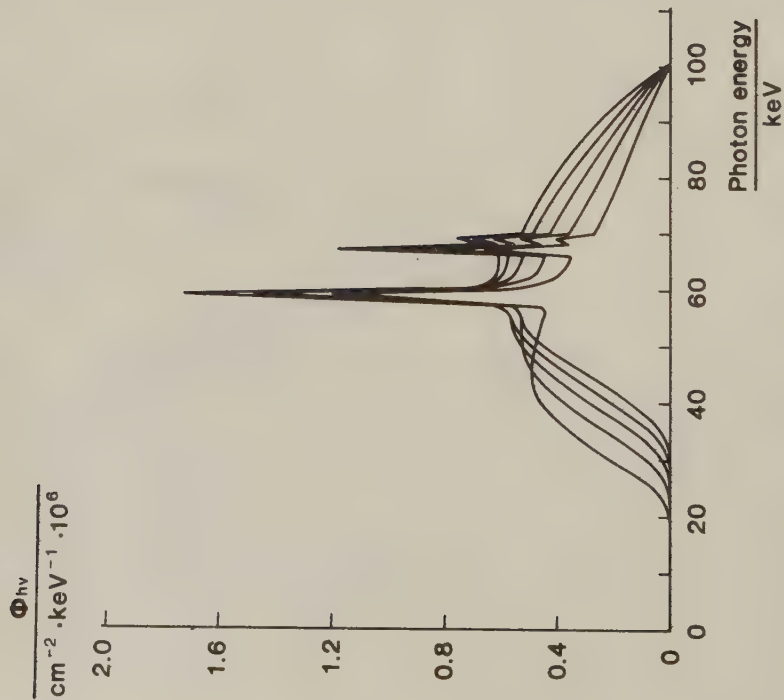


Figure 5. Photon distributions transmitted through 5, 10, 15, 20 and 25 mm aluminium at x-ray tube potential 100 kV.

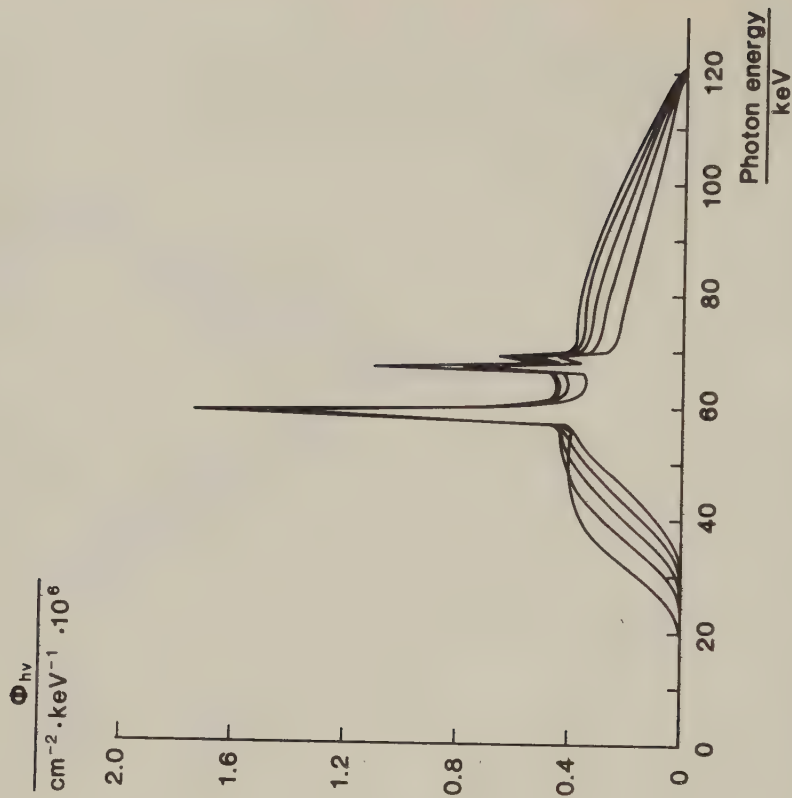


Figure 6. Photon distributions transmitted through 5, 10, 15, 20 and 25 mm aluminium at x-ray tube potential 120 kV

The coefficient for converting x-ray exposure to photon fluence,  $(\phi/X)_{x,y}$ , at the radiation quality produced at x kV filtered with y mm aluminium is derived from:

$$(\phi/X)_{x,y} = (W_{air}/e) \cdot \frac{\int_{h\nu \min}^{h\nu \max} (\frac{d\phi}{dh\nu})_{x,y} dh\nu}{\int_{h\nu \min}^{h\nu \max} (\frac{d\psi}{dh\nu})_{x,y} \cdot (\mu_{en}/\rho)_{air} dh\nu} \tag{4}$$

### 3. RESULTS AND DISCUSSION

Table 1 presents the x-ray exposure to photon fluence conversion coefficients at the various radiation distributions.

Table 1

| Exposure to photon fluence conversion coefficient |                      |       |        |        |
|---------------------------------------------------|----------------------|-------|--------|--------|
| $cm^{-2} \cdot \mu C^{-1} \cdot kg \cdot 10^7$    |                      |       |        |        |
| Al filter                                         | X-ray tube potential |       |        |        |
|                                                   | 60 kV                | 80 kV | 100 kV | 120 kV |
| 5 mm                                              | 7.02                 | 8.38  | 9.04   | 9.28   |
| 10 mm                                             | 8.02                 | 9.38  | 9.85   | 9.88   |
| 15 mm                                             | 8.63                 | 9.93  | 10.26  | 10.13  |
| 20 mm                                             | 9.04                 | 10.28 | 10.48  | 10.24  |
| 25 mm                                             | 9.35                 | 10.52 | 10.62  | 10.28  |

These conversion coefficients are slightly lower, but within -2.5 % of the coefficients published by Mika and Reiss (1973).

The coefficients for converting x-ray exposure to energy fluence are presented in Table 2.



Table 2

| <u>Exposure to energy fluence conversion coefficient</u>                            |                      |       |        |        |
|-------------------------------------------------------------------------------------|----------------------|-------|--------|--------|
| $\text{keV} \cdot \text{cm}^{-2} \cdot \mu\text{C}^{-1} \cdot \text{kg} \cdot 10^9$ |                      |       |        |        |
| Al filter                                                                           | X-ray tube potential |       |        |        |
|                                                                                     | 60 kV                | 80 kV | 100 kV | 120 kV |
| 5 mm                                                                                | 2.87                 | 4.12  | 5.03   | 5.72   |
| 10 mm                                                                               | 3.50                 | 4.94  | 5.86   | 6.49   |
| 15 mm                                                                               | 3.91                 | 5.46  | 6.36   | 6.94   |
| 20 mm                                                                               | 4.22                 | 5.84  | 6.71   | 7.25   |
| 25 mm                                                                               | 4.26                 | 6.12  | 6.97   | 7.48   |

In Figure 7, these conversion coefficients are plotted versus the thickness of the aluminium filter. Except for the elementary charge and the mean energy for production of one ion pair in air, which are constants, it is obvious from Equations 3 and 4 that the energy absorption properties of air are determinant for the conversion coefficients. According to Equation 3, the coefficients for converting x-ray exposures to energy fluences are equal to the quotients between a constant factor and the mass energy absorption coefficients of air weighted according to the energy fluence distributions. These weighted mass energy absorption coefficients of air are presented in Table 3.

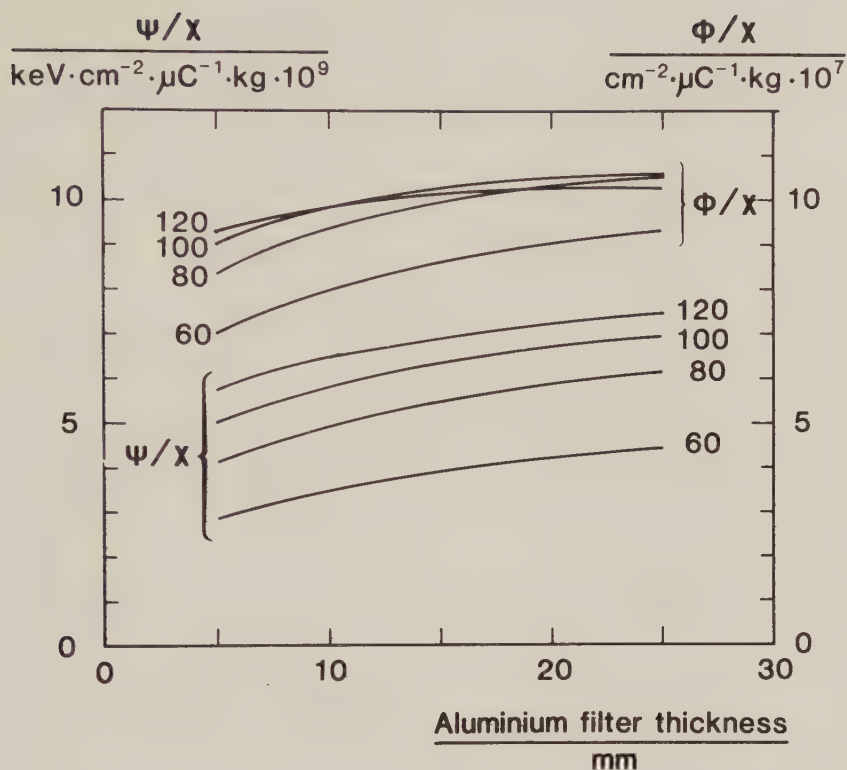


Figure 7. Coefficients for converting x-ray exposure to energy fluence,  $\Psi/X$ , and to photon fluence,  $\Phi/X$ , for broad x-ray distributions. These are produced at the x-ray tube potentials 60, 80, 100 and 120 kV and with various aluminium filter-thicknesses.

Table 3

| Weighted mass energy absorption coefficients of air |                      |       |        |        |
|-----------------------------------------------------|----------------------|-------|--------|--------|
| $\text{cm}^2 \cdot \text{g}^{-1}$                   |                      |       |        |        |
| Al filter                                           | X-ray tube potential |       |        |        |
|                                                     | 60 kV                | 80 kV | 100 kV | 120 kV |
| 5 mm                                                | 0.073                | 0.051 | 0.042  | 0.037  |
| 10 mm                                               | 0.060                | 0.043 | 0.036  | 0.032  |
| 15 mm                                               | 0.054                | 0.038 | 0.033  | 0.030  |
| 20 mm                                               | 0.050                | 0.036 | 0.031  | 0.029  |
| 25 mm                                               | 0.047                | 0.034 | 0.030  | 0.028  |

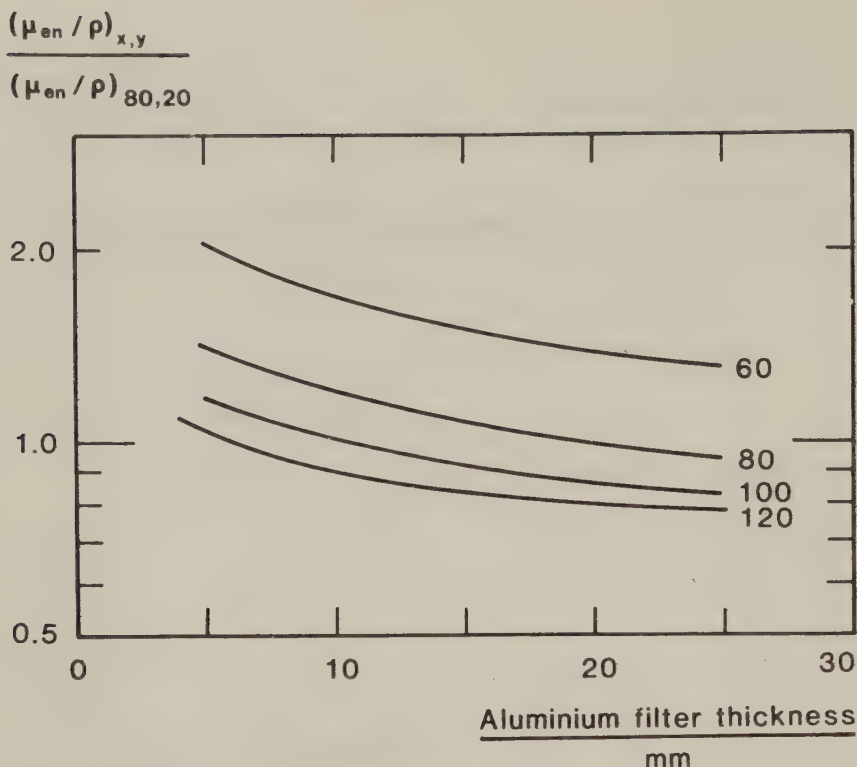


Figure 8. Weighted mass energy absorption coefficients at various energy fluence distributions relative to that at 80 kV filtered with 20 mm aluminium.  $x$  denotes x-ray tube potential, and  $y$  denotes the aluminium filter thickness used to produce these energy fluence distributions.

Figure 8 presents the weighted mass energy absorption coefficients of air at the various radiation distributions relative to that at 80 kV filtered with 20 mm aluminium. In spite of the logarithmic presentation, it is easy to see the inverse relationship between the relative weighted mass energy absorption coefficients of air in Figure 8 and the exposure to energy fluence conversion coefficients in Figure 7.

The weighted mass energy absorption coefficients in Table 3 provide for interesting comparisons with the mass energy absorption coefficients of air for monoenergetic radiation (Hubbell, 1969). Such a comparison reveals for example, that the weighted mass energy absorption coefficient at 80 kV filtered with 20 mm aluminium is equivalent to that for 54.5 keV photons. One can therefore conclude that the energy absorption in air of the

photon distribution produced at 80 kV filtered with 20 mm aluminium is equivalent to that of photons with 54.5 keV energy.

## REFERENCES

Hubbell J.H. (1969) Photon Cross Sections, Attenuation Coefficients and Energy Absorption Coefficients from 10 keV to 100 keV. National Stand. Ref. Data. Ser., National Bureau of Standards (U.S.), 29, Washington, D.C., 20234.

Mika N and Reiss K.H. (1973) Tabellen zur Röntgendiagnostik Teil I, Siemens Aktiengesellschaft, Bereich Medizinische Technik, Entwicklungsabteilung, Erlangen.

Svahn G. (1977) Diagnostic x-ray spectra. Thesis, Radiation Physics Dept., University of Lund, Lund, Sweden.







Printing  
Pehr Johnson  
Lund 1983